Medium Energy Nuclear Physics Research at the University of Richmond

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Abstract

The nuclear physics program at the University of Richmond is focused on the structure of nucleons and the transition from the hadronic picture of matter to a quark-gluon description. We will use the Thomas Jefferson National Accelerator Facility (JLab) to measure the charge and current distributions of the neutron and extract components of the deuteron wave function. In experiment E12-07-104 (spokesperson: Gilfoyle) we will measure the neutron magnetic form factor at high momentum transfer. We are now part of the group developing software to reconstruct, simulate, and analyze the data from the new CLAS12 detector at JLab.

1 Project Introduction

This is a renewal application to support the University of Richmond electromagnetic nuclear physics research program at the Thomas Jefferson National Accelerator Facility (JLab). Dr. G.P. Gilfoyle is the principle investigator (PI) and the physics projects are listed in Table 1. The University of Richmond is a primarily undergraduate institution and there are no graduate students in physics. The group has a joint program with the University of Surrey in the UK to support a masters student to do research at JLab. During this grant period the group typically consisted of the PI and 2-3 undergraduates. In 2013, a masters student, Mr. Alexander Colvill from the University of Surrey performed his masters research work in our group.

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
Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)	CLAS-Approved Analysis[1]
CLAS12 Software	
Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)	E12-06-117
Precision measurement of the neutron magnetic form factor up to $Q^2 = 18\ (\mathrm{GeV}/c)^2$ by the ratio method	E12-09-019

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

We now summarize our progress in the three years since our last renewal (2011). The program was reviewed in June 2013, as part of DOE's Nuclear Physics Comparative Review. The research of 170 university groups and 30 national laboratory groups was assessed on the basis of equally-weighted evaluation criteria. The Richmond group passed the review and, given the group's size, its output was 'rather impressive' and showed 'Strength in bringing undergrads to research.'

Our main focus now is on preparations to measure G_M^n, the neutron magnetic form factor. A broad program at JLab will measure all the elastic, electromagnetic form factors - six experiments

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[1] The CLAS Collaboration has a procedure where Collaboration members can analyze existing data sets with official Collaboration approval. The member writes a proposal describing an analysis project, it is reviewed by an internal committee, and then defended before the full Collaboration.

including two to measure G_M^n. The PI (Gilfoyle) is spokesperson and contact person for the G_M^n experiment in Hall B using the new CLAS12 detector (E12-07-104) and is a co-spokesperson on the Hall A measurement (E12-09-019). Both experiments use methods pioneered in Hall B with the previous CLAS6 detector [1]. The PI is a lead author on that work.

Much of our work is now in software to prepare for the start of operations of CLAS12. We have written the code to reconstruct events in the Forward and Central Time-Of-Flight counters (FTOF and CTOF) in CLAS12 [2]. The FTOF is an important part of the G_M^n measurement for detecting both electrons and neutrons. The code is written in Java and can be deployed as a software service in CLARA, the CLAS12 reconstruction framework [3]. Both packages have been validated in software stress tests of the full CLAS12 reconstruction code (Section 2.1.1 and References [2, 4, 5]). We have extended and improved the simulation of the CLAS12 Electromagnetic Calorimeter in the physics-based, Monte Carlo simulation of CLAS12 (*gemc*). Gilfoyle is the original author of the code and we have made it more realistic, robust, and transparent. Our EC geometry CLAS12-NOTE is being used as a model for others to develop geometry services (Section 2.1.1 and Reference [6]). We are investigating the use of the Intel Xeon Phi to increase the speed of the CLAS12 event reconstruction. With CLAS12 we will collect 5-10 TB of data per day. The Phi is a co-processor that can perform highly parallel computations and was able to perform simplified track fitting more than an order of magnitude faster than its host computer (Section 2.1.1 and Reference [7]). We have also updated, streamlined, and enhanced an event generator for quasielastic scattering from the deuteron used in our simulations (Section 2.1.1 and References [8] and [9]).

We continue to push forward on our measurement of the fifth structure of the deuteron in the $^2\mathrm{H}(\vec{e}, e'n)n$ reaction done with CLAS6, the previous Hall B detector. The fifth structure function gives us access to the spin-orbit part of the nucleon-nucleon interaction and these data at low-Q^2 test our existing knowledge of the hadronic model of nuclei. The work has been submitted for internal CLAS Collaboration review and we are working through the committee recommendations (Section 2.1.2).

The PI continues to contribute to the software planning process for CLAS12. Jefferson Lab has set the goal for the software group to be able reconstruct, simulate, and analyze the datastream in a timely fashion from the start of data taking in CLAS12. The PI was a contributor to the CLAS12 Software Technical Design Report [10] and has presented different parts of the program during software reviews (Section 2.1.3 and References [11, 12]).

We now summarize our Plan of Work. The main focus will continue to be on preparations for the G_M^n experiment and associated software development. The PI will be on sabbatical during the 2015-2016 academic year and is making arrangements for spending the sabbatical at JLab. This will be during the period just before commissioning of CLAS12 in Hall B so he will be well-positioned to contribute to the startup of the detector. During the period of this proposal we will more fully develop our existing simulation of the dual-cell target for E12-07-104 and will take on part of the CLAS12 track-based alignment project. We plan to complete the Collaboration review of the analysis of the $^2\mathrm{H}(\vec{e}, e'n)n$ reaction to extract the fifth structure function of the deuteron.

We request funds to support masters students in a joint program between Richmond and the University of Surrey in the UK (Section 2.3). Undergraduates from Surrey are selectively admitted to the masters program and required to spend one year doing research. These students' work is matched to their interests, the program here, and the research at JLab. The addition of these students (one per year) would enhance our productivity and the learning experience for the Richmond undergraduates in our group. The Surrey program has been successful in the nuclear structure community at Yale, Kentucky, Florida State, Notre Dame, LBL, and even Richmond (through a faculty colleague, Dr. Con Beausang). Those programs benefited from the Surrey students and many of these students have gone on to US graduate schools, enhancing the US workforce.

2 Project Description

2.1 Status of Current Projects

The research effort in medium energy nuclear physics at the University of Richmond is part of the program at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA. Here we summarize our physics and technical projects.

2.1.1 Magnetic Form Factor of the Neutron

The elastic electromagnetic form factors are basic observables that describe the distribution of charge and magnetization inside the proton and neutron. Their measurement is a goal of the current NSAC Long-Range Plan [13], it is Milestone HP4 in the DOE Performance Measures [14], and it forms a central part of the future physics programs at Jefferson Lab (JLab) [15, 16, 17]. We are part of a broad campaign to measure the four elastic, electromagnetic, nucleon form factors (electric and magnetic ones each for the proton and neutron) at JLab that include six experiments approved for running after the 12 GeV Upgrade at JLab is complete (Section 2.2 and References [16, 17]). Gilfoyle is the spokesperson and contact person for JLab experiment E12-07-104 to measure G_M^n, the neutron magnetic form factor in Hall B using the CLAS12 detector now being built. The experiment has an A^- rating from the Program Advisory Committee (PAC) and was awarded 30 days of beamtime to be scheduled in the first five years running of CLAS12. Much of our work revolves around preparations for CLAS12 operations in general and the G_M^n measurement in particular. We are also members of the collaboration to measure G_M^n in Hall A (E12-09-019).

We now discuss our work to prepare for the new CLAS12 detector and for the G_M^n measurement. CLAS12 consists of a Forward Detector with a toroidal field generated by six sectors of superconducting coils. An array of drift chambers, time-of-flight counters, Cerenkov counters, calorimeters, and other devices to measure and identify the reaction products [18]. The Central Detector covers large angles and is built around a solenoid magnet and another suite of detectors. In 2011, we made a commitment to the 'design, prototyping, development, and testing of software for event simulation and reconstruction in CLAS12' as part of a Memorandum of Understanding with JLab. The importance of software development in preparation for the start of the 12 GeV era has grown. JLab Director Hugh Montgomery has stated publicly the goal of being able to analyze and calibrate data from turn-on. In an internal JLab review of the computing enterprise at the Laboratory in May, 2011, the review committee stated that 'it is the desire of the laboratory to have all computing systems and software ready, so that the time from beam on target to physics journal articles is as short as possible' [19, 20, 21, 22, 23]. We are committed to reaching that goal.

We have written the reconstruction code for the CLAS12 Forward and Central Time-Of-Flight subsystems (FTOF and CTOF). The FTOF is built from arrays of scintillation paddles that are grouped into panels. See the left-hand panel of Figure 1. In each sector there are two similar, triangular panels arranged back-to-back (FTOF Panels 1a and 1b). Panel 1b is closest to the target. A third panel (Panel 2) is located at large angles. The FTOF produces a fast timing signal for triggering the data acquisition and, when combined with data from the other subsystems, is essential for particle identification. It is an important part of the G_M^n measurement for detecting both electrons and neutrons. The CTOF is made of 48 paddles that form a hermetic barrel around the target in the Central Detector. See the right-hand panel in Figure 1.

Written in Java, the new software runs in the CLAS12 Reconstruction and Analysis Framework (CLARA) [24]. CLARA is based on a Service-Oriented Architecture (SOA) and the CTOF and FTOF applications are written as software services. A service here is a software component (i.e. a piece of code or a data structure) that is reusable and where the access is provided using a well-

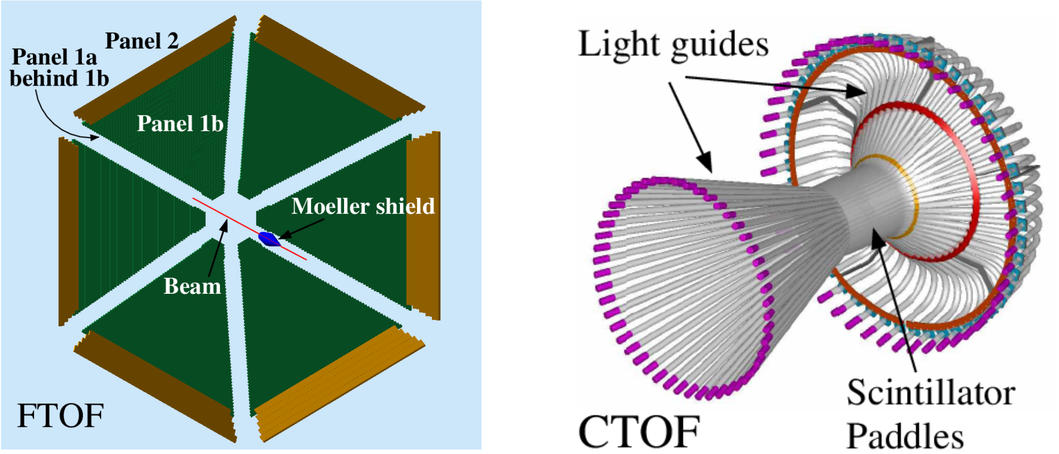

Figure 1: Forward (left) and Central (right) time-of-flight (TOF) panels.

defined interface. These TOF services are included in the CLAS12 reconstruction chain and were part of software stress tests performed over the last two years. The time-of-flight reconstruction code performed as expected. This project formed the masters thesis for a student, Alexander Colvill, from the University of Surrey in the UK. Mr. Colvill is the first student from Surrey to work at JLab as part of the joint Richmond/Surrey program discussed in Section 2.3. His thesis was published as a CLAS-NOTE and he received highest honors in the UK for his thesis defense. The first year of the Richmond/Surrey program at JLab was a success.

Simulation of the CLAS12 detector was used to design these software services, test them, and study the CLAS12 response. For example, we have studied how to optimize the way that particle hits on adjacent scintillation paddles are combined into clusters. Figure 2 shows the percentage of events as a function of the number of paddles that were triggered in FTOF panels 1a and 1b. Recall panel 1b is the same size and is located in front of panel 1a so particles that trigger 1b will likely trigger 1a. The plot demonstrates that hitting more than two paddles is relatively rare (about 1% of time) and incoming particles are more likely to trigger more paddles in panel 1b than in panel 1a. These multiple hits can come from a 'corner clipper' where a straight track enters one paddle at a large angle to the normal at the face of the paddle and cuts across one paddle and enters an adjacent one. To trigger more than two paddles rescattering between the incident particles and the scintillator material will deflect the primary particles to larger angles and trigger more paddles. This change in the mechanism for triggering paddles is apparent in the change in the slope at $N = 3$ in panel 1b in Figure 2. Panel 1b has narrower paddles than panel 1a. With more narrow paddles, panel 1b has a larger fraction of its area near the paddle edges and scattered particles traverse more paddles for a given trajectory.

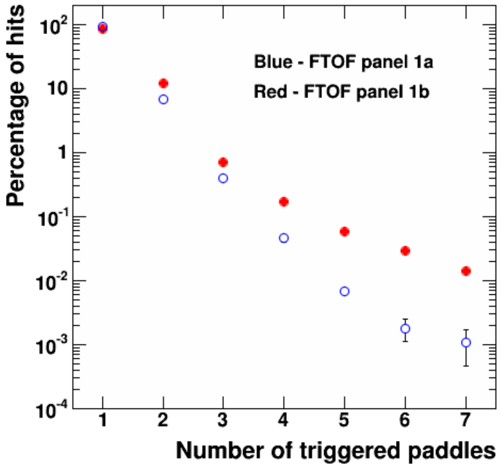

Figure 2: Percentage of incoming particles triggering N paddles.

We have also extended our work on the electromagnetic calorimeter (EC). The EC is the main neutron detector for the G_M^n experiment along with the FTOF mentioned above. Gilfoyle implemented the EC simulation in *gemc* in 2009 including the geometry. The EC consists of alternating layers of lead and plastic scintillator (39 scintillator layers) with each scintillator layer formed by 36 strips. One of the approximations made in the first version of the geometry was to treat each scintillator layer as a large slab and then impose the strip geometry during digitization. This approach was used in CLAS6, the pre-Upgrade detector in Hall B. We replaced that method with the full strip geometry and observed a 5-8% increase in the average CPU-time per event (more data to manage in the simulation). We also saw a a modest impact on the graphics performance. The updated geometry and codes are described in a CLAS12-NOTE that is being used as a model for other CLAS12 sub-system groups [6]. This work was done by the PI and one undergraduate.

We are investigating the use of the Intel Xeon Phi co-processor as a tool to speed the data reconstruction, simulation, and analysis. CLAS12 will collect data at a high rate - about 5-10 TB per day. The Phi is a co-processor with sixty cores and uses the Many-Integrated Core (MIC) architecture. It adds considerable computing power to its host machine. We obtained a Phi with grant funds after consulting with Chip Watson, head of the JLab High-Performance Computing group, and Ted Barnes, the DOE Medium Energy program manager at that time. Two of our undergraduates (Justin Ruger and Keegan Sherman) have programmed the Phi and observed large increases in computing speed. Mr. Ruger used the Phi to perform a partial-wave analysis of reaction data [25]. Mr. Sherman used a Kalman filter to extract track parameters from a simplified set of data representing a charged particle's trajectory in a magnetic field [7]. This work was done by the PI with these students and Dennis Weygand from JLab.

To prepare for operations with CLAS12 and the G_M^n experiment requires a realistic event generator to simulate the reaction with *gemc*. We have developed such a program. We started with a C^{++} code written for the CLAS6 G_M^n measurement called QUEEG [26]. We updated the program and its libraries and added several new options. We simplified the overly complex build system to make it more maintainable. The code is documented in a CLAS12-NOTE and stored in the CLAS12 repository [8, 9]. This project was done by the PI and one undergraduate.

It is worth commenting here on our change of plans from the 2011 renewal. At that time we proposed beginning target development for the CLAS12 G_M^n experiment and studying neutron detection in the CLAS12 calorimeters. We made modest progress on the target simulation during this grant period with the QUEEG event generator [8, 9]. At the beginning of 2013 we decided to switch to the TOF reconstruction software project. The FTOF is one of the key components in the CLAS12 $G_M^n n$ measurement (E12-07-104); it will be used for both electron and neutron detection (see Section 2.2.1). The CLAS12 Software Group had the reconstruction framework (CLARA, see Reference [24]) and some of the software components working including the calorimeter reconstruction, but there was no TOF reconstruction code. After consulting with the members of the CLAS12 Software Group (D.Weygand was leader of the group at that time) and realizing the Surrey student had excellent computing skills, we decided to focus on the TOF reconstruction project. It was simply a higher priority than the studies of the calorimeter. Our decision was also influenced by changes in the CLAS12 startup schedule.

2.1.2 Out-of-Plane Structure Functions of the Deuteron

We are investigating the out-of-plane structure functions of the deuteron using the $^2\text{H}(\vec{e}, e'p)n$ reaction to establish a baseline for the hadronic model of nuclei to meet. The data were measured with the CLAS6 detector at JLab and consist of two data sets both at a beam energy of 2.6 GeV, but with opposite torus magnet polarities so they cover different Q^2 ranges. CLAS6 is the previous, Hall B detector and shares many aspects with CLAS12. It is a large, toroidal, multi-gap magnetic spectrometer with nearly full solid angle coverage, the same, six-sector geometry and a similar array of detectors. This hadronic model baseline is necessary to map the transition from hadronic to quark-gluon degrees of freedom at higher Q^2 (see NSAC Long-Range Plan [13]). We are extracting the fifth structure function which is the imaginary part of the LT interference and has not been studied extensively in the past. The cross section for the $^2\mathrm{H}(\vec{e}, e'p)n$ reaction with a polarized beam and unpolarized target can be written as

$$\frac{d\sigma^3}{d\nu d\Omega_e d\Omega_{pq}} = \sigma_L + \sigma_T + \sigma_{TT}\cos\phi_{pq} + \sigma_{LT}\cos 2\phi_{pq} + h\sigma'_{LT}\sin\phi_{pq} \tag{1}$$

where the σ_i are the components of the cross section and $h = \pm 1$ is the electron beam helicity. The angle ϕ_{pq} is the angle between the plane defined by the incoming and outgoing electron 3-momenta and the plane defined by the ejected proton and the 3-momentum transfer $\vec{q}$. The structure functions are studied by forming asymmetries from the data. Here we define the helicity asymmetry as $A'_{LT} = \sigma'_{LT}/(\sigma_L + \sigma_T)$ where σ'_{LT} is the partial cross section of the fifth structure function and σ_L and σ_T are the longitudinal and transverse parts.

During this grant period we have made significant changes to the analysis. We have revised the method for selecting quasielastic events. Instead of using the peak at the nucleon mass in W, the mass recoiling against the scattered electron, we used W_n defined as

$$W_n^2 = M_d^2 - 2M_d E_p + m_p^2 + 2(M_d - E_p)\nu - Q^2 + 2|\vec{p}_p||\vec{q}|\cos\theta_{pq} \tag{2}$$

where M_d is the deuteron mass, E_p is the detected proton energy, m_p is the proton mass, ν is the energy transfer, $\vec{p}_p$ is the detected proton 3-momentum, $\vec{q}$ is the 3-momentum transfer, and θ_{pq} is the angle between $\vec{p}$ and $\vec{q}$. This method takes full advantage of the measured electron and proton 4-momenta. The cutoff for quasielastic events is $W_n < 1.04$ GeV, 3σ below the pion threshold where σ is the W_n resolution extracted from the width of the quasielastic peak. Figure 3 shows some of our preliminary results with this new approach as a function of $|\vec{p}_m|$, the missing momentum $\vec{p}_m = \vec{q} - \vec{p}_p$. To extract A'_{LT} we use the $\sin\phi_{pq}$-weighted moments of the data corrected for the beam polarization P_e and beam charge asymmetry A_Q as shown in Equation 3.

$$A'_{LT} = \frac{1}{P_e A_Q}\left(\langle\sin\phi_{pq}\rangle_+ - \langle\sin\phi_{pq}\rangle_-\right) \quad \text{where} \quad \langle\sin\phi_{pq}\rangle_\pm = \frac{\int_0^{2\pi}\sigma^\pm \sin\phi_{pq} d\phi_{pq}}{\int_0^{2\pi}\sigma^\pm d\phi_{pq}} \tag{3}$$

The bar graph in Figure 3 shows the size of the systematic uncertainty on A'_{LT}. The asymmetry itself shows a significant dip near $p_m = 0.22$ MeV/c that disappears at larger missing momentum.

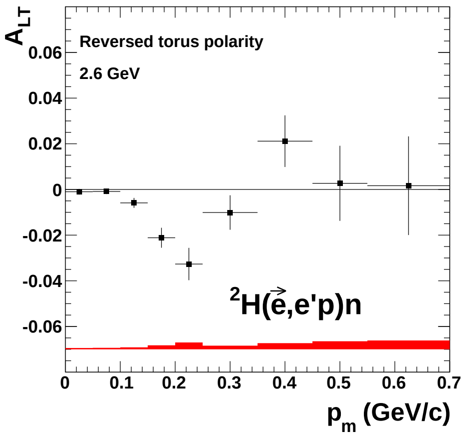

Figure 3: Preliminary results for A'_{LT}.

A CLAS Analysis Note has been submitted to the CLAS Collaboration. This is the first step in the process to approve the results for publication. A Collaboration committee reviews the document and requests revisions. We have gone through several exchanges with the committee and are now working through their recommendations. One of the requests called for revisions to the the simulations we performed to validate our analysis methods. We incorporated the asymmetry into the QUEEG event generator (see Section 2.1.1) and simulated the data with the CLAS6 physics-based simulation GSIM. We analyzed the simulated results with the same code we used to analyze the data. We see good agreement between the bin-averaged input and the asymmetry extracted from the simulation. We validated our analysis for one CLAS6 torus magnet polarity and began calculations for the other one. We completed additional tests extracting the asymmetry in a different way using fits to the ϕ_{pq} dependence [27, 28] and obtained good agreement with the results in Figure 3. This work was done by the PI and an undergraduate [27, 28].

2.1.3 CLAS12 Software Planning

The CLAS12 detector will have prodigious computing requirements. With the high luminosity ($10^{35} cm^{-2} s^{-1}$) we expect to collect about 10^{11} events each year requiring a batch farm with more than 12,000 cores to perform the reconstruction, simulation, and other analysis and keep pace with the incoming datastream. The goal is to be ready to analyze data when beam arrives [19, 20]. At Richmond we have taken on software tasks needed to make CLAS12 a success and we have also taken a leadership role in planning and preparing for the 12 GeV era. The PI was one of the contributors to the CLAS12 Software Document [29]. He calculated the CLAS12 computing hardware requirements, vetting the results to stakeholders, and checking consistency with other halls. He was also responsible for describing different aspects of the software enterprise at two reviews of the CLAS12 Software Group during this grant period [11, 12].

2.1.4 University of Richmond Physics Computing Cluster

Central to the productivity of our group at Richmond is the maintenance of a physics computing cluster. The system consists of 31, 2.66 GHz, dual-6-core, remote nodes each with 24 GByte of RAM and 1 TByte of storage. The head node is a 2.66 GHz, dual-6-core machine also with 24 GByte of RAM. A file server provides 5 TByte of space. The system was used for nearly all projects described here and has been the one of the main development tool for CLARA [3, 30].

2.1.5 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and the quest to understand confinement is an essential goal of nuclear physics. Confinement can be studied by striking a quark with a photon and stretching out the color string tying it to its neighbors. Gilfoyle is co-spokesperson on JLab experiment E12-06-117 *Quark Propagation and Hadron Formation* that lays out a program to determine the mechanisms of confinement in forming systems. We will be responsible for the analysis of the π^0, η, and η' exit channels. The experiment was reviewed by PAC36 and received a scientific rating of A$^-$ and was allocated 60 days of beamtime.

2.1.6 Summary

Since our last review in 2011 our program was successfully reviewed by the DOE Nuclear Physics Comparative Review. We have made progress on preparations for the G_M^n experiment, the start of the 12 GeV era at JLab, and the construction of the CLAS12 detector. We have written the reconstruction services for both time-of-flight subsystems in CLAS12 (Central and Forward detectors) that are now part of the overall CLAS12 reconstruction package. We have improved the simulation of the CLAS12 electromagnetic calorimeter (EC) with more realistic scintillator geometry and updated and documented the EC geometry calculations. We made significant changes to our analysis of the fifth structure function of the deuteron and submitted a CLAS Analysis Note for internal, collaboration review. We have been fully engaged in the CLAS12 software planning process and reviews. We have explored new technologies to reconstruct our data faster and updated and enhanced an event generator for the G_M^n experiment.

2.2 Plan of Work

The research effort here in nuclear physics is part of the program at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA. The primary goal of JLab is to unravel the quark and gluon structure of protons, neutrons, and atomic nuclei and to understand how they emerge from Quantum Chromodynamics (QCD). In this section we describe the experimental environment and the proposed physics programs. Gilfoyle will spend his sabbatical during 2015-2016 at JLab.

JLab is a unique tool for basic research in nuclear physics. The central instrument is the Continuous Electron Beam Accelerator Facility (CEBAF); a superconducting electron accelerator with a maximum energy of 12 GeV, a 100% duty cycle, and a maximum current of $\approx 85\ \mu$A. JLab is near completion of the 12 GeV Upgrade project to double the beam energy, enhance the existing experiment halls, and construct a new detector in Hall D (see the left-hand panel in Figure 4). Commissioning of Hall D started in October, 2014 with the new, 12-GeV CEBAF. Completing the Upgrade is the highest priority in the current NSAC Long-Range Plan [13]. CLAS12 in Hall B is a large particle detector with a toroidal, multi-gap magnetic spectrometer with nearly full solid angle coverage at forward angles (the Forward Detector) and a large solenoid centered on the target for large angles (the Central Detector). See the right-hand panel in Figure 4. There are over 60,000 readout channels. The toroidal magnetic field in the Forward Detector is generated by six sectors of iron-free superconducting coils. The particle detection system in each sector consists of drift chambers [31] to measure charged particle trajectories, Cerenkov detectors [32] to identify electrons, scintillators [33] for time-of-flight measurements, and electromagnetic calorimeters [34]. The six segments are instrumented individually to form six independent spectrometers. The Central Detector is built around a solenoid magnet with a silicon tracker, time-of-flight system and Central Neutron Detector for particle detection. The Richmond group has been part of the CLAS Collaboration since its inception.

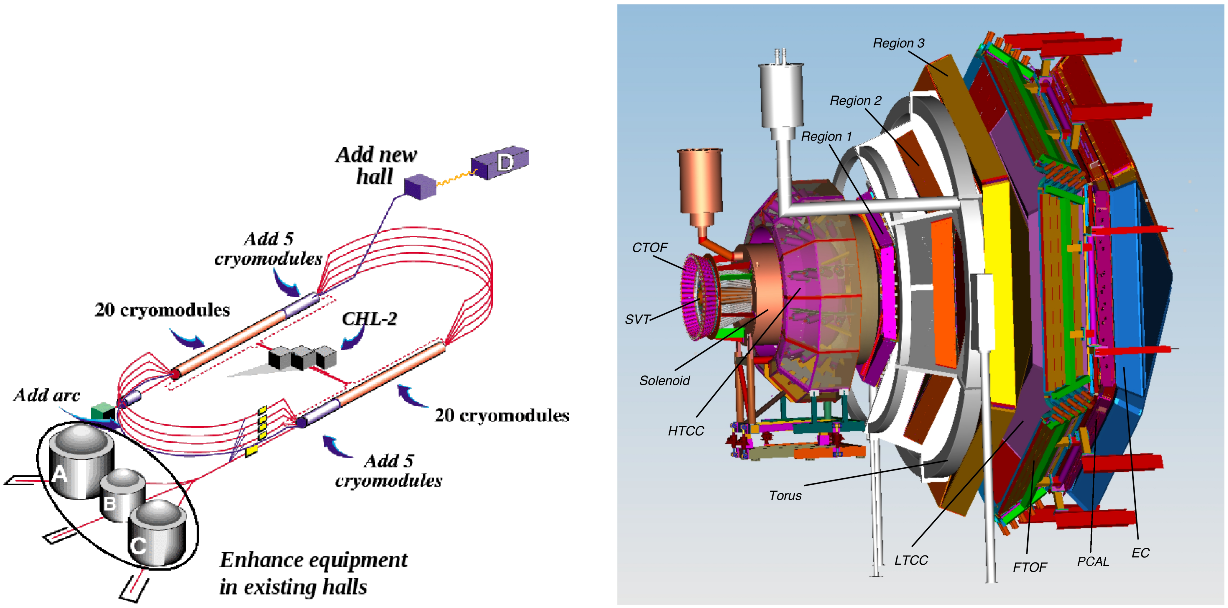

Figure 4: CEBAF layout (left) and CLAS12 design drawing (right).

Our focus for the next three years is primarily on preparations for the start of operations of the CLAS12 detector, its commissioning, and initial running. We are also part of the G_M^n experiment in Hall A. Neither experiment has yet been scheduled. In this section we will describe our program on (1) the G_M^n measurements in Halls A and B (emphasis on Hall B), (2) software development for CLAS12, (3) the analysis of the fifth structure function, (4) our participation in the JLab experiment E12-06-117 *Quark Propagation and Hadron Formation*, and (5) other components of our research.

2.2.1 Magnetic Form Factor of the Neutron

We now describe our program to measure the neutron magnetic form factor G_M^n at high Q^2. One of the central goals of nuclear physics now is to push our understanding of QCD into the nonperturbative region [13]. Here, the nonlinear nature of QCD dominates and defies traditional mathematical solutions; forcing us to resort to phenomenological models, effective field theories, and the daunting numerical calculations of lattice QCD. Our understanding of the structure of the proton and neutron is still clouded. The neutron magnetic form factor G_M^n is one of the fundamental quantities of nuclear physics and its evolution with Q^2 characterizes the distributions of charge and magnetization within the neutron. It is central to our understanding of nucleon structure as discussed in the NSAC Long-Range Plan [13] and in Milestone HP4 in the DOE Performance Measures [14]. We are part of a broad campaign to measure the four elastic nucleon form factors (electric and magnetic ones each for the proton and neutron) at JLab that include six experiments approved for running after the 12 GeV Upgrade at JLab is complete [16, 17].

Our role in this campaign is twofold. First, Gilfoyle is the spokesperson and contact person for JLab Experiment E12-07-104 which will measure G_M^n with the CLAS12 detector in Hall B and was approved by JLab PAC32. He is also a co-spokesperson on a Hall A measurement of G_M^n E12-09-019. For the next budget period our focus will be on the CLAS12 experiment. We propose to develop software for simulating the CLAS12 detector and analyzing the results. The JLab management and the CLAS Collaboration recognize that we must be ready to collect, calibrate, and analyze data from CLAS12 at start-up to produce physics results in a timely manner [19, 20, 21]. The projects we describe below are aimed at both preparing for E12-07-104 and fulfilling this Collaboration and Laboratory goal. Second, working with the JLab staff we will begin development of the unique, dual-cell target for the G_M^n measurement (see below). CLAS12 startup is expected in mid-2016 so target preparations should begin in the next funding period. We had planned to start the target development in the current grant period, but changes in the CLAS12 schedule and new demands on software development took increased priority.

Measuring G_M^n and other other elastic form factors will decisively impact our understanding of the nucleon in the 12-GeV era. We expect to obtain a new, unprecedented tomographic view of the interior of the nucleons through measurement of generalized parton distributions (GPDs). The elastic form factors are a limiting case of the GPDs and provide a vital constraint on GPD models [35]. Lattice QCD calculations are now becoming feasible in the few-GeV^2 range, and over the next decade these calculations will become increasingly precise [36]. The elastic form factors for both the proton and neutron are an important, early test case of the accuracy of the lattice calculations. With all four of them, one can extract the isovector combination of the form factors [37] which are easier to calculate on the lattice because they lack disconnected contributions [38].

The discovery potential of the G_M^n measurement is shown in Fig 5. The reduced form factor $G_M^n/\mu_n G_D$ is plotted versus Q^2 where G_D is the dipole form factor $G_D(Q^2) = 1/(1 + Q^2/\Delta)^2$ and $\Delta = 0.71$ GeV^2. A selection of the world's data is shown by the open, green squares. The CLAS6 G_M^n measurement is shown by the open, red circles [1]. The anticipated results for E12-07-104 are shown in the closed, black squares. The bar graphs show the measured (CLAS6 in red) and anticipated (CLAS12 in black) systematic uncertainties. The E12-07-104 measurements will reach out to $Q^2 \approx 13$ (GeV/c)^2, more than doubling the range of the high-precision measurements. The anticipated Hall A results are the blue, open squares. The two theory curves illustrate different attempts to describe the data: a constituent quark model using the light-front formalism (long-dashed curve from Miller [46]) and a calculation based on the Dyson-Schwinger equation (dashed curve from Cloet *et al.* [47]). The calculations diverge for $Q^2 > 6$ (GeV/c)^2; above the range of nearly all the existing data. The planned G_M^n measurement will have the precision to distinguish between them.

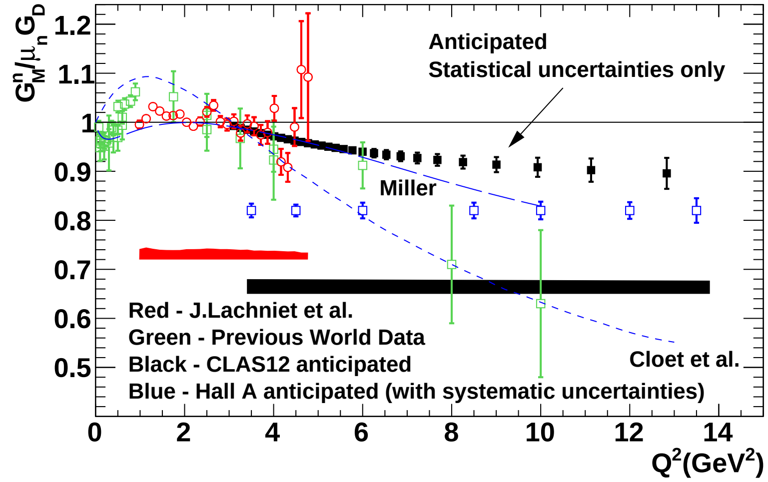

Figure 5: Results for $G_M^n/(\mu_n G_D)$ from CLAS6 (red), previous data (green) [39, 40, 41, 42, 43, 44, 45], theoretical calculations, and expected data from CLAS12 (black) are shown.

To measure G_M^n we use the ratio R of $e-n$ to $e-p$ quasielastic (QE) scattering from a deuterium target (there are no free neutron targets). We will use the same method in the CLAS12 measurement that was used in the CLAS6 one [1]. The differential cross section for elastic electron-nucleon scattering can then be calculated in the lab frame as [48]

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)\left(\frac{1}{1+\tau}\right) \tag{4}$$

where σ_{Mott} is the cross section for scattering from a point particle, G_E is the electric form factor, G_M is the magnetic form factor, $\tau = Q^2/4M^2$ where M is the nucleon mass, and the virtual photon polarization is $\epsilon = (1 + 2(1+\tau)\tan^2(\theta/2))^{-1}$ where θ is the electron scattering angle. To obtain G_M^n we use the ratio R

$$R = \frac{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'n)p\right)_{QE}}{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'p)n\right)_{QE}} = a(E,Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2\tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2\tan^2(\frac{\theta}{2})} \tag{5}$$

where E is the beam energy and $a(E,Q^2)$ corrects for nuclear effects which can be calculated from deuteron models and is close to unity at large Q^2. To select QE events we require θ_{pq}, the angle between the detected nucleon and 3-momentum transfer $\vec{q}$ to be small which eliminates most inelastic events near the QE peak [1]. This technique can be applied equally well to both proton and neutron events - reducing biases in the analysis by using the same method for both nucleons. By taking the ratio R we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction and trigger efficiencies, the deuteron wave function, and radiative corrections [1, 49, 50]. The extraction of G_M^n depends on our knowledge of the other three nucleon form factors, but the proton form factors are precisely known and the neutron's electric form factor G_E^n is typically small so its impact on the systematic uncertainty is limited. This technique does require precise knowledge of the neutron detection efficiency and careful matching of the neutron and proton acceptances. To measure the neutron detection efficiency a unique dual-cell, co-linear, liquid-hydrogen-liquid-deuterium target will be used. The $ep \to e'\pi^+n$ reaction is a source of tagged neutrons which are detected in two, overlapping measurements with both the electromagnetic calorimeter (EC) and the forward time-of-flight (FTOF) system - providing a powerful consistency check on the measurements. To measure the proton detection efficiency we use elastic *ep* scattering on the hydrogen target. Acceptance matching is done event-by-event by detecting the electron, assuming QE scattering, and calculating the track for both proton and neutron. If both particles are expected to strike the active area of the detector, we continue with the analysis, otherwise the event is rejected. Corrections for nucleon Fermi motion in the deuteron are simulated. The methods described here were successful in our previous analysis of the CLAS6 E5 data [1].

For the CLAS12 G_M^n experiment we found that an additional requirement was needed to control the inelastic background. At these higher Q^2 the width of inelastic scattering increases and encroaches on the quasielastic region. The left-hand panel in Figure 6 shows this effect along with the much greater inelastic cross section relative to the QE events. The red histogram is from QE events, the green one is from inelastic events, and the blue one is their sum. We can remove most of this background by applying cuts on proton and neutron angles (θ_{pq} in Figure 6) to select QE events and rejecting inelastic ones that produce additional particles in the final state. The large, solid-angle coverage of CLAS12 is crucial here. The result is shown in the right-hand panel of Figure 6.

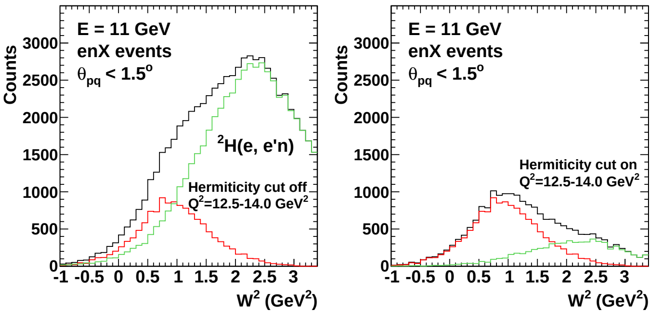

Figure 6: The effect of requiring no additional particles in the final state (hermiticity cut) is shown in the highest Q^2 bin where the inelastic contamination will be greatest.

To prepare for the CLAS12 G_M^n experiment we propose to begin target development during the next funding period. In the current schedule physics running will begin in mid-2016 and it typically takes about one year to develop a target like the one needed here. It is prudent to begin those preparations during the next funding period which runs to May, 2018 to be ready for possible early physics running of the CLAS12 G_M^n experiment. As mentioned above we will use a dual-cell target so that production running and calibrations (*i.e.* measurement of the neutron detection efficiency) can be done under the same running conditions. In Figure 7 we show a potential design. An upstream (left) cell will hold liquid deuterium for production running and the downstream (right) cell will hold liquid hydrogen for calibrations. The cryo-liquid cells in each design are conical to allow any bubbles formed by heating from the beam to flow out of the target. The design was inspired by our experience with the CLAS6 G_M^n experiment and other targets. The cooling lines and support structures will be attached at the upstream end of the target to minimize the material in the path of scattered particles. In the design here each cell is 2 cm long with a 2 cm gap in between the cells.

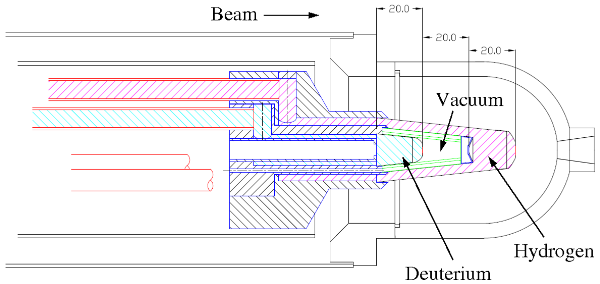

Figure 7: G_M^n target design drawing. Dimensions are in *mm*.

During the next grant period we will begin design studies to optimize the target performance. These studies require an event generator for QE events from deuterium that includes the effects of the Fermi motion. We have this feature in the QUEEG program that was used in the CLAS6 G_M^n experiment and which we have updated and improved (see Section 2.1.1). In the past we have used the program GENEV to generate inelastic events [51]. We will also need a simulation of the target cell that can be incorporated into the CLAS12, physics-based simulation *gemc*. We have already taken the first steps toward this goal and have developed the geometry for an earlier design[52]. The next steps will be to generate the geometry for this design and add support structures, supply tubes, *etc.*

There are a number of issues to address in the target design. The dual-cell target is used to perform *in situ* calibrations to measure the proton and neutron detection efficiencies under the same running conditions as the production measurements. One difference between the calibration and production targets is their position. We know from CLAS6 (which had a much longer target) these effects could be significant. The smaller target size in CLAS12 should reduce this effect, but we want to investigate it now in simulation and consider strategies like performing runs with the target moved upstream to put the calibration target in the production target position, putting the cryo-liquids in different cells, *etc.*

There are other issues that we will study in simulation to design the target. Very forward angle QE events from the deuterium cell can pass through the hydrogen one and effect the scattering. The length and position of each cell and hence the size of the gap requires adequate position resolution to separate events from the different cells. The expected position resolution in CLAS12 is 1 mm, the cells in Figure 7 are 2 cm apart (many standard deviations). The impact of different materials and thicknesses in the cell walls, *etc.* will be studied. Our experience with CLAS6 showed the dominant source of multiple scattering is the drift chambers, but we should inventory all the contributions and see where reductions in thicknesses could be made while maintaining the structural integrity of the target. Many of these issues can change at large scattering angles where one samples different parts of the CLAS12 detector. The backgrounds can also change as the kinematics change. We will investigate these issues. Reference [53] has a full discussion of many of this issues for the CLAS6 E5 target. We have discussed the target development with the Dr. V. Burkert, the Hall B Leader, who agreed our timing for the project is appropriate. We have already started discussions with D. Kashy, S. Christo, and C. Keith and the engineering staff in Hall B. It is worth mentioning that investigating these issues will provide an important test for the CLAS12 reconstruction code now under development. We expect to have the full set of tools for event reconstruction in the Forward Detector available in the next six months - just as this project is starting. Validating the CLAS12 reconstruction software requires a variety of projects like this one to challenge the code with a wide range of kinematics and event topologies. It will also, obviously, help us prepare for the G_M^n experiment.

2.2.2 CLAS12 Software Development and Planning

We are part of the team developing software for CLAS12 in preparation for the start of experimental running in 2016. The goal is to be ready to analyze data when beam arrives [19, 20]. The computing requirements for CLAS12 are large and for the Collaboration to successfully analyze data at startup requires accurate, adaptable, and efficient code. Our role in this project is twofold. (1) We are developing software to simulate and analyze CLAS12 data (see Section 2.2.1 and below) and (2) Gilfoyle is part of the CLAS12 software planning team.

In developing this Plan of Work we met with the leader of the CLAS12 Software Group (JLab staff scientist V. Ziegler) and the other members of the group to discuss priorities, unassigned tasks, and the the steps necessary to meet the Laboratory goal. Considering the current schedule for CLAS12 startup (mid-2016) and the fact that the PI (Gilfoyle) will be on sabbatical during the year before startup we have decided to focus on track-based alignment for CLAS12. Reaching the CLAS12 design specifications requires understanding the geometry of the detector components as they are built and installed and during their operation. Differences between the nominal geometry and the detector built in Hall B can degrade the resolution and lead to systematic biases in the reconstruction of the data. These difference could effect the physics results. This task is more important for the new CLAS12 detector relative to the previous one because of the increased segmentation of some components (Silicon Vertex Tracker (SVT), panel 1b of the FTOF, *etc.*). Our focus here will be on track-based alignment as opposed to complementary tasks like surveying. The alignment is important for the G_M^n experiment (Section 2.2.1). In the dual-cell target the liquid hydrogen and deuterium cells may only be 2 cm apart (see Figure 7) requiring the resolution in the z position of the scattered electron vertex to meet the design specification of 1 mm.

The motivation for the alignment project is that the actual positions of detector components (drift chamber wires, silicon strips) may differ from the nominal, design values - causing the reconstruction software to return flawed values for the track parameters. To align CLAS12 we start by considering two general approaches to this problem - iterative and closed form. In the iterative approach, a track model (*e.g.*, a solution to the passage of a charged particle through a magnetic field) is fit to the hit positions from the detector by minimizing the χ^2 defined in the usual way as the sum of residuals normalized by the uncertainty. The residual distributions generated by performing this step for many tracks are used to adjust the geometry of the detector (the residuals should average to zero) and the process is repeated until the χ^2 converges to a satisfactory value. This technique is less complex than others, but does not include the impact of correlations. For many detectors the parameters of the fitted track are correlated with changes to the detector geometry. Consider, for example, three regions of drift chambers like the ones used in the CLAS12 Forward Detector. If the region closest to the target is offset from the nominal geometry during installation so it is farther from the beam line, then a straight track that goes through all three will have different track parameters than one where the drift chambers were at their design positions. The displaced region will have a biased, nonzero average residual, but so will the adjacent regions making it ambiguous how to adjust the detector positions to get the average residual to go to zero.

In the closed form approach a least squares fit is performed simultaneously on the track parameters and the detector geometry parameters so it naturally accounts for correlations. However, for a detector like CLAS12 the number of detector parameters is large so the computational demands may be prohibitive. However, there are possible solutions. One is Millipede II, a program for linear least squares fits with a large number of parameters based on the minimization of the χ^2 [54, 55, 56]. The method takes advantage of the difference between local parameters (fit parameters for individual tracks) and global ones (the positions, orientations, deformations, *etc* of the detector components). This difference manifests itself in the structure of the least squares matrix so all the information from the local (track) fits can be included in the matrix that consists of the global (detector) parameters - significantly decreasing the size of the problem. This matrix equation is then solved by inversion and the inverse matrix is the covariance matrix of the global parameters. Fits with as many as 100,000 global parameters are possible [56].

Regardless of the approach there are two primary issues to consider in our alignment program. (1) The 'weak modes' problem is one where some of the eigenvectors extracted from the fits have small eigenvalues that have little impact on the χ^2. In other words, different local (track) parameters have nearly the same χ^2. This ambiguity in the local parameters can effect the physics results. To mitigate this problem requires a large sample of events (both simulated and real) from a wide range of topologies that adequately illuminate all parts of CLAS12. The alignment program should use cosmic rays (that do not go through the target region), straight tracks ($\vec{B} = 0$), and bent ones ($\vec{B} \neq 0$) over a wide range of kinematics. (2) The other issue is validation of the alignment results. The χ^2 should be well behaved and the residuals should be largely independent of the fit parameters. A residual that increases with, for example, the azimuthal angle ϕ is a sign the alignment is off. The track results should also be tested with 'standard candles' - properties of events that are independent of tracking. These properties could be the energy and cross section of elastic scattering, invariant masses and widths of known resonances, or cosmic rays that traverse two sectors of CLAS12 (the two tracks should be the same). One can also alter, in simulation, the position of detector elements in a known way to see if the alignment system captures that change. One may also use multiple methods to align CLAS12 (closed form versus iterative) and compare the results.

The plan of work for this project is the following. We will start by selecting one of the approaches discussed above in consultation with the JLab staff and members of the CLAS12 Software Group. Simulations of tracks in the CLAS12 Forward Detector will be used to develop the code to align the detector. Validation of the software will be done with simulated events using the methods described above. In the next phase, as construction of CLAS12 nears completion we will challenge the software with cosmic ray data. Some CLAS12 subsystems are already taking cosmic ray data (forward TOF, calorimeters) so these data should will be available before CLAS12 startup. The goal in all this work is to be able provide accurate, precise global alignment parameters by the time CLAS12 begins production running. The code will operate as a service in the CLARA framework.

We will continue our work in other projects. The TOF reconstruction code is far along, but not complete. Many of the future developments will be done with one of our collaborators from Moscow State University (MSU), Dr. E. Golovach. He has started working on the matching of hits in the two back-to-back forward TOF panels (panels 1a and 1b, see Figure 1) with the particle trajectory from the drift chamber reconstruction. This work is necessary to reach the final design goal of a timing resolution of 80 *ps* at forward angles in the FTOF. We will be working with Dr. Golovach and testing the code in the other projects described here (target simulation and alignment). In Section 2.1.1 we presented results from our application of the Intel Xeon Phi co-processor to CLAS12-related projects. We will continue developing and testing code that uses the Phi in ways that could benefit the physics program. The undergraduate Physics/Computer Science student (K.Sherman) who has been working on that project will continue to work in my research group for the next two years and we are also taking advantage of the expertise at JLab with the Phi [57, 7]. Software planning will part of our work for the next funding period as we have in the past [10, 11, 12, 21].

2.2.3 Out-of-Plane Structure Functions of the Deuteron

We propose to measure the quasielastic (QE), out-of-plane, structure functions of the deuteron in the GeV region to test the hadronic model of nuclei. The hadronic model of nuclear physics has been successful at low Q^2, but it is not well-developed in the GeV region even though we expect it to be valid there. There are few data to challenge theory - only three measurements for QE events, all at lower Q^2 [58, 59, 60]. The importance of relativistic corrections (RC), final-state interactions (FSI), meson-exchange currents (MEC), and isobar configurations(IC) is our focus here. Testing the hadronic model establishes a baseline necessary to answer one of the questions posed in the most recent NSAC Long-Range Plan: 'What governs the transition from quarks and gluons to pions and nucleons?' [13]. The importance of this issue was stressed in previous JLAB PAC studies [61].

We are investigating these out-of-plane structure functions of the deuteron using the reaction $^2\mathrm{H}(\vec{e}, e'p)n$ with CLAS6. See Section 2.1.2 for the expression for the cross section and the kinematic observables. The structure functions are the meeting ground between theory and experiment and the unique, nearly-4π solid angle of CLAS6 coupled with the high-quality, polarized beams at JLab create an inviting opportunity to study σ'_{LT} - the partial cross section related to the imaginary part of the longitudinal and transverse interference. We are essentially making a model-independent measurement of a little-studied part of the deuteron cross section that probes its wave function.

In the next grant period we will work to complete the CLAS Analysis Note now under CLAS Collaboration review (Section 2.1.2). The work requested by the review committee is to re-analyze the data in new kinematic variables. Instead of Q^2, Bjorken x_{Bj}, and missing momentum p_m, we would recast the analysis in Q^2, x_{Bj}, and $\cos\theta_{nq}$, the angle between the 3-momentum transfer $\vec{q}$ and the missing 3-momentum $\vec{p}_m$. We will also revise the comparison of our measured asymmetry with theory. We may be able to do this by rebinning our existing data or, if necessary, apply theory to create a sample of events used as input to the CLAS6, physics-based simulation GSIM. Our data analysis codes would then be run to extract the theory A'_{LT} results for comparison, integrating theory and analysis into the same framework. We will also revise our radiative corrections. The cut on W_n (see Equation 2) used to select QE events will be related to the parameters used to make the radiative corrections [62] and to the revised set of kinematic variables discussed above to study the impact of the radiative corrections.

2.2.4 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and its understanding is a central challenge in nuclear physics. We will investigate the nature of confinement by studying the hadronization process across a wide range of nuclei. This will enable us to extract the quark production times (*i.e.*, the lifetime of a bare, struck quark) and the hadron formation times (*i.e.* the time for a hadron to become fully dressed with its gluon field). These physics goals are focused on one of the central questions raised by the NSAC Long-Range Plan [13] 'What governs the transition of quarks and gluons into pions and nuclei?'. Experiment E12-06-117 was approved by PAC30 and earned a scientific rating of A^- from PAC36 in 2010 [63]. Gilfoyle is a co-spokesperson on the proposal and is responsible for analysis of the π^0, η, and η' channels along with K. Joo from the University of Connecticut. During the period of this grant we will continue work on the simulation of events in CLAS12. More details on software development can be found in Sections 2.2.1-2.2.2.

2.3 Masters Student Support

We request in this proposal funding to support a masters-level student who will be engaged in the physics projects described here. The physics program in the next funding period is centered around preparations for the CLAS12 G_M^n measurement and the start of data taking in CLAS12. Our focus is on developing software for simulation and analysis that will also have an impact on the overall physics program for CLAS12. Our group at the University of Richmond consists of a single faculty member and 2-4 undergraduates working during the summers. The addition of a 10-month masters student would raise our productivity and enhance the intellectual environment in our research group and in the Physics Department at the University of Richmond.

The University of Richmond is a primarily undergraduate institution and the Physics Department does not usually have graduate students. The proposed masters student would be part of a joint program between Richmond and the University of Surrey in the UK. Undergraduate physics majors at Surrey normally graduate in three years, but some apply and are selected to receive a masters degree in physics that includes a year of research. These are the students who would be funded by this program. In physics skills they are equivalent to first-year graduate students in the United States. The program director at Surrey, Prof. P. Stevenson, is enthusiastic about the opportunity for their masters students to do research at JLab (see link to letter from Dr. Stevenson in Reference [64] and Appendix A). We request funds only for an annual stipend; there are no tuition costs.

We have thought carefully about how to structure this student's experience. (1) We would station the person in the Richmond office at Jefferson Lab. Gilfoyle routinely travels to JLab (see Section 2.5); he spends about 60 days each year on site so there would be ample time for for collaboration. Gilfoyle is an active member of the CLAS12 Software group and the group provides a good working environment and community to work in. Three of the JLab staff scientists (Ziegler, Gyurjyan, Ungaro) in the group are committed to supporting this student. (2) The student would spend some time (1-2 days per month) in Richmond typically on the Physics Department's seminar days. This would broaden the students' perspective by working in a university setting, interacting with Richmond undergraduates, and collaborating with the PI. In this proposal we ask for funding for this travel. (3) The program proposed here covers a significant range of topics from analysis of CLAS6 data to developing new tools for CLAS12. We will work closely with the our collaborators at JLab and at Surrey to match the students' skills and interest to the needs of the program. We received funding for this position as a supplement to this grant in 2012 and Mr. Alexander Colvill spent 2013 working at JLab. He was responsible for writing the first version of the CLAS12 time-of-flight reconstruction code (Section 2.1.1). This was a significant contribution to the CLAS12 software effort that filled a glaring hole at the time. Mr. Colvill graduated with high honors and his thesis was published as a CLAS12-NOTE [2]. A letter voicing support for this program from Dr. V.Ziegler, the leader of the CLAS12 Software Group, is in Reference [65] and Appendix B. Dr. Ziegler described the program as "an excellent source of scientific talent". This is an exciting time at JLab and the program outlined here would embed the student in that community, provide abundant opportunities for working with the PI, and also give the student a taste of a university environment.

It is worth mentioning this collaboration with Surrey has been a success in the nuclear structure community at Yale, Kentucky, Florida State, Notre Dame, LBL, and even Richmond (through a faculty colleague, Dr. Con Beausang). Those programs benefited from the Surrey students and many of the students have gone on to US graduate schools, enhancing the US workforce. We also point out that stationing the masters student at JLab dramatically cuts the overhead rate.

2.4 Undergraduate Research at the University of Richmond

Undergraduates are part of all stages of this physics program and the funds requested will enable us to provide an intense summer research experience for these young people. Since 1987 Gilfoyle has mentored 2-3 undergraduates doing research almost every summer with about two-thirds going on to graduate school in science and engineering at places like UNC - Chapel Hill, UC Santa Barbara, Virginia, Princeton, and Stanford. Five have received doctorates. Three from our lab are currently staff scientists at NASA-Goddard, NASA-Huntsville, and the Jet Propulsion Laboratory, one is a faculty member at Stanford, and one is a researcher at Cornell in biological physics. Among students who worked in our laboratory over the last five years one (Mark Moog) is now in graduate school in physics at Chapel Hill, another (Matt Jordan) is in graduate school in electrical engineering at Georgia Tech, Calina Copos is a graduate student in applied mathematics at UC, Irvine and Justin Ruger is a masters student at Christopher Newport University. Three have taken lucrative positions in industry that use the skills they learned working in our laboratory. Our students use modern computational techniques for simulation and to 'mine' large data sets for information using our super computing cluster. They take shifts at JLab, attend collaboration meetings, present their work at local, national, and international conferences [4, 7, 9, 25, 27, 28, 52, 57], and are co-authors on technical reports [2, 6, 8, 66, 67]. In the last three years six different students worked in my laboratory including a high school student who is now a physics major at Richmond. They were funded by a mixture of DOE grant and University funds.

2.5 Institutional Support and Resources

The PI (Gilfoyle) will be on sabbatical during the 2015-2016 academic year which coincides the the year before commissioning of CLAS12. He is pursuing support for a full-year sabbatical and for travel from several sources including this proposal.

The nuclear physics group at the University of Richmond is supported by a computing cluster obtained in 2010 with an NSF MRI grant. See Section 2.1.4 for more details. An array of student workstations is used for software development and non-CPU-intensive tasks all in the Physics Department research area. This cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can sit in the JLab queue more than a day before submission. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm. The University information technology staff maintains the cluster.

The University also supports undergraduate summer stipends and student travel. We have had 1-2, university-supported undergraduates working in our laboratory for each of the last three years. The student posters cited in Section 2.4 had travel support from the University, the American Physical Society, and the current DOE contract. The University will support routine faculty travel to JLab at the level of ≈$3,500 per year for the PI. The University has started a new policy of returning 10% of indirect costs from external grants back to the PI.

Jefferson Lab is 75 miles from Richmond enabling us to maintain frequent contacts with the scientific staff and users. The PI spends about 1 day each week at JLab in addition to time spent on shift, at Collaboration meetings, *etc.* We take students on shift and attend Collaboration meetings at little cost.

2.6 Summary

We now summarize our Plan of Work for the next grant period. Our research is centered on the medium energy program at Jefferson Lab, in particular on the upcoming measurement of the neutron magnetic form factor with CLAS12. In the next grant period we will develop a full simulation of the target for the experiment including studies of the CLAS12 response to optimize the target design. We will also begin the process for building the target at JLab. We are also committed to the developing software for the simulation, reconstruction, and analysis of data from CLAS12. We will investigate ways to align CLAS12 and continue to study ways to apply the Intel Xeon Phi co-processor for CLAS12 physics. The involvement of the PI in software planning will continue as the Collaboration considers ways to make the software enterprise more efficient.

Our study of the fifth structure function of the deuteron is far along and we will continue responding to the advice of the CLAS Collaboration review committee. We request funds for a masters student to support this program and enhance our productivity and the intellectual environment for our undergraduate researchers and the Physics Department at Richmond. As usual, undergraduates will be involved in all phases of the program we describe here.

3 References

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3 Publications Since Last Review

Refereed Journals

The first set of publications are ones where Gilfoyle had considerable input as co-author and chair/member of the CLAS Collaboration review committee.

1. B. Dey et al. Data analysis techniques, differential cross sections and spin density matrix elements for the reaction $\gamma p \rightarrow \phi p$. *Phys.Rev.*, C89:055208, 2014.
2. M. Moteabbed et al. Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering. *Phys.Rev.*, C88:025210, 2013.
3. H. Egiyan et al. Upper limits for the photoproduction cross section for the Phi–(1860) pentaquark state off the deuteron *Phys.Rev.*, C85:015205 2012.
4. A. Daniel et al. Measurement of the nuclear multiplicity ratio for K0s hadronization at CLAS. *Phys.Lett.*, B706:26, 2011.

The second set below are publications where Gilfoyle had a standard contribution in terms of CLAS service work, offering suggestions during the comment period for the Collaboration review, *etc.*

1. Y. Prok et al. Precision measurements of g_1 of the proton and the deuteron with 6 GeV electrons. *Phys.Rev.*, C90:025212, 2014.
2. W. Gohn et al. Beam-spin asymmetries from semi-inclusive pion electroproduction. *Phys.Rev.*, D89:072011, 2014.
3. S. Tkachenko et al. Measurement of the structure function of the nearly free neutron using spectator tagging in inelastic ^{2}H(e, e'p)X scattering with CLAS. *Phys.Rev.*, C89:045206, 2014.
4. K. Moriya et al. Spin and parity measurement of the $\Lambda(1405)$ baryon. *Phys.Rev.Lett.*, 112(8):082004, 2014.
5. M. Dugger et al. Beam asymmetry Σ for π^+ and π^0 photoproduction on the proton for photon energies from 1.102 to 1.862 GeV. *Phys.Rev.*, C88(6):065203, 2013.
6. K. Moriya et al. Differential Photoproduction Cross Sections of the $\Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$. *Phys.Rev.*, C88:045201, 2013.
7. W. Tang et al. Cross sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ reactions measured at CLAS. *Phys.Rev.*, C87:065204, 2013.
8. K. Moriya et al. Measurement of the photoproduction line shapes near the (1405). *Phys.Rev.*, C87(3):035206, 2013.
9. O. Hen et al. Measurement of transparency ratios for protons from short-range correlated pairs. *Phys.Lett.*, B722:63–68, 2013.
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11. P. Khetarpal et al. Near Threshold Neutral Pion Electroproduction at High Momentum Transfers and Generalized Form Factors. *Phys.Rev.*, C87(4):045205, 2013.
12. K. Park et al. Deep exclusive π^+ electroproduction off the proton at CLAS. *Eur.Phys.J.*, A49:16, 2013.
13. M. Anghinolfi et al. Comment on the narrow structure reported by Amaryan et al. 2012.
14. H. Baghdasaryan et al. A comparison of forward and backward pp pair knockout in 3He(e,e'pp)n. *Phys.Rev.*, C85:064318, 2012.
15. L. El Fassi, L. Zana, K. Hafidi, M. Holtrop, B. Mustapha, et al. Evidence for the Onset of Color Transparency in ρ^0 Electroproduction off Nuclei. *Phys.Lett.*, B712:326–330, 2012.
16. K. Park et al. Measurement of the generalized form factors near threshold via $\gamma^* p \to n\pi^+$ at high Q^2. *Phys.Rev.*, C85:035208, 2012.

Technical Reports (*denotes undergraduate co-author, †masters student)

1. A.Colvill† and G.P.Gilfoyle, "Time of Flight Software for the CLAS12 Detector ", CLAS-NOTE 2014-013, Jefferson Lab, 2014.
2. G.P.Gilfoyle, J.D.Lachniet and O.Alam*, "QUEEG: A Monte Carlo Event Generator for Quasielastic Scattering on Deuterium", CLAS-NOTE 2014-007, Jefferson Lab, 2014.
3. G.P.Gilfoyle and K.Sherman*, "Geometry Update for the Electromagnetic Calorimeter in CLAS12", CLAS-NOTE 2014-008, Jefferson Lab, 2014.
4. D. Weygand, G.P. Gilfoyle, et al. "CLAS12 Software Document - Hall B 12 GeV Upgrade", Technical report, Jefferson Lab, 2012.

Proceedings and Abstracts (*denotes undergraduate co-author, †masters student)

1. K. Sherman* and G.P. Gilfoyle. Investigating the Use of the Intel Xeon Phi for Event Reconstruction. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2014.
2. K. Sherman* and G.P. Gilfoyle. A Deuteron Quasielastic Event Simulation for CLAS12. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2014.
3. A. Colvill† and G.P. Gilfoyle. Forward Time of Flight Reconstruction Software for CLAS12. In *Bull. Am. Phys. Soc., Fall SESAPS Meeting*, 2013.
4. J. Ruger*, G.P. Gilfoyle, and D. Weygand. Applicability of Parallel Computing to Partial Wave Analysis. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2013.
5. L. Murray* and G.P. Gilfoyle. Validating the Analysis Algorithms to Extract the Helicity Asymmetry in the 2H(e ,ep)n Reaction. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2013.
6. L. Murray* and G.P. Gilfoyle. Extracting the Fifth Structure Function of the $^2\mathrm{H}(\mathrm{e}, \mathrm{e}'\mathrm{p})\mathrm{n}$ Reaction. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2012.
7. K. Sherman* and G.P. Gilfoyle. Simulation of the Scintillator Geometry in the Electromagnetic Calorimeter in the CLAS12 Detector. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2012.

4 Principal Collaborators

I have worked with many members of the CLAS Collaboration over the years. A listing of the full collaboration is available at the following website.

`https://clasweb.jlab.org/membership/phonebookA.php`

The list below includes members of the Collaboration that I have worked with closely over the last four years and others outside the Collaboration.

Mac Mestayer	William Brooks	Evgeny Golovach
Lawrence Weinstein	Michael Vineyard	Andrei Afanasev
David Jenkins	Jeffrey Lachniet	Latifa Elouadrhiri
Veronique Ziegler	J.W. Van Orden	Hartmuth Arenhövel
John Arrington	Mark Ito	Gagik Gavalian
Dennis Weygand	Kawtar Hafidi	Maurizio Ungaro
David Heddle	Graham Heyes	S.E.Kuhn

The remaining members of the CLAS Collaboration are listed below.

A. Klimenko	S. Gilad	P.E. Bosted	K.V. Dharmawardane
G.E. Dodge	T.A. Forest	Y. Prok	G. Adams
M. Amarian	P. Ambrozewicz	M. Anghinolfi	G. Asryan
H. Avakian	H. Bagdasaryan	N. Baillie	J.P. Ball
N.A. Baltzell	S. Barrow	V. Batourine	M. Battaglieri
K. Beard	I. Bedlinskiy	M. Bektasoglu	M. Bellis
N. Benmouna	A.S. Biselli	B.E. Bonner	S. Bouchigny
S. Boiarinov	R. Bradford	D. Branford	S. Buhltmann
V.D. Burkert	C. Butuceanu	J.R. Calarco	S.L. Careccia
D.S. Carman	B. Carnahan	A. Cazes	S. Chen
P.L. Cole	P. Collins	P. Coltharp	P. Corvisiero
D. Crabb	H. Crannell	V. Crede	J.P. Cummings
R. De Masi	R. DeVita	E. De Sanctis	P.V. Degtyarenko
H. Denizli	L. Dennis	A. Deur	C. Djalali
J. Donnelly	D. Doughty	P. Dragovitsch	M. Dugger
S. Dytman	O.P. Dzyubak	H. Egiyan	P. Eugenio
R. Fatemi	G. Fedotov	R.J. Feuerbach	H. Funsten
M. Garcon	G. Gavalian	K.L. Giovanetti	F.X. Girod
J.T. Goetz	E. Golovatch	A. Gonenc	R.W. Gothe
K.A. Griffioen	M. Guidal	M. Guillo	N. Guler
L. Guo	V. Gyurjyan	C. Hadjidakis	K. Hafidi

R.S. Hakobyan	J. Hardie	F.W. Hersman	
K. Hicks	I. Hleiqawi	M. Holtrop	M. Huertas
C.E. Hyde-Wright	Y. Ilieva	D.G. Ireland	B.S. Ishkhanov
E.L. Isupov	H.S. Jo	K. Joo	H.G. Juengst
C. Keith	J.D. Kellie	M. Khandaker	K.Y. Kim
K. Kim	W. Kim	A. Klein	F.J. Klein
M. Klusman	M. Kossov	L.H. Kramer	V. Kubarovsky
J. Kuhn	S.V. Kuleshov	J. Lachniet	J.M. Laget
J. Langheinrich	D. Lawrence	Ji Li	A.C.S. Lima
K. Livingston	H. Lu	K. Lukashin	M. MacCormick
N. Markov	B. McKinnon	J.W.C. McNabb	C.A. Meyer
T. Mibe	K. Mikhailov	R. Minehart	M. Mirazita
R. Miskimen	V. Mokeev	L. Morand	S.A. Morrow
M. Moteabbed	G.S. Mutchler	P. Nadel-Turonski	J. Napolitano
R. Nasseripour	S. Niccolai	G. Niculescu	I. Niculescu
B.B. Niczyporuk	M.R. Niroula	R.A. Niyazov	M. Nozar
G.V. O'Rielly	M. Osipenko	A.I. Ostrovidov	K. Park
E. Pasyuk	C. Paterson	S.A. Philips	J. Pierce
N. Pivnyuk	D. Pocanic	O. Pogorelko	E. Polli
S. Pozdniakov	B.M. Preedom	J.W. Price	D. Protopopescu
L.M. Qin	B.A. Raue	G. Riccardi	G. Ricco
M. Ripani	F. Ronchetti	G. Rosner	P. Rossi
D. Rowntree	F. Sabatie	C. Salgado	J.P. Santoro
V. Sapunenko	R.A. Schumacher	V.S. Serov	Y.G. Sharabian
J. Shaw	N.V. Shvedunov	A.V. Skabelin	E.S. Smith
L.C. Smith	D.I. Sober	A. Stavinsky	S.S. Stepanyan
B.E. Stokes	P. Stoler	S. Strauch	R. Suleiman
M. Taiuti	S. Taylor	D.J. Tedeschi	U. Thoma
R. Thompson	A. Tkabladze	S. Tkachenko	L. Todor
C. Tur	M. Ungaro	A.V. Vlassov	A. Freyburg
M. Williams	M.H. Wood	A. Yegneswaran	J. Yun
L. Zana	J. Zhang	B. Zhao	Z. Zhao

5 Biographical Sketch: Dr. Gerard P. Gilfoyle

Degrees

Ph.D., University of Pennsylvania, 1985 - ‘Resonant Structure in $^{13}\mathrm{C}(^{13}\mathrm{C},^{4}\mathrm{He})^{22}\mathrm{Ne}$’, H.T. Fortune, advisor.
A.B., cum laude, Franklin and Marshall College, 1979.

Experience

2008-present - Denoon Professor of Science, University of Richmond.
2004-present - Professor of Physics, University of Richmond.
2002-2003 - Scientific Consultant, Jefferson Laboratory.
1999-2000 - Defense Policy Fellow, American Association for the Advancement of Science.
1994-1995 - Scientific Consultant, Jefferson Laboratory.
1993-2004 - Associate Professor of Physics, University of Richmond.
Summer, 1988 - Visiting Research Professor, University of Pennsylvania.
1987-1993 - Assistant Professor, University of Richmond.
1985-1987 - Postdoctoral Research Fellow, SUNY at Stony Brook.

Research and Teaching Grants

1990-present - US Department of Energy ($1.7M in ten awards).
2014-present - JSA/SURA Initiatives Fund award ($10,000).
2009-2011 - National Science Foundation MRI grant ($162,000).
2009-2010 - JSA/SURA Sabbatical Support ($13,500).
2009-2010 - JSA/SURA Initiatives Grant ($7,500).
2002-2003 - SURA Sabbatical Support ($10,000).
2002-2003 - Jefferson Laboratory Sabbatical Support ($28,335).
2001-2002 - National Science Foundation research grant ($175,000).
1995-1997 - National Science Foundation teaching grant ($14,986).
1994-1995 - CEBAF Sabbatical Support ($24,200)
1992-1995 - National Science Foundation teaching grant ($49,813).

Selected Service

2013 - Chair CLAS Collaboration nominating committee
2005-present Reviewer, US Department of Energy and National Science Foundation.
2006-2010 - Chair, Nuclear Physics Working Group of the CLAS Collaboration
2006-2010 - CLAS Coordinating Committee
2005-present - Reviewer for JSA/SURA Graduate Fellowships and Initiatives Funds.
2005-present - Reviewer for American Association for the Advancement of Science.
2000-2006 - Chair, Department of Physics.
1993-1999, 2001-present - Ethyl, Oldham, Science Scholarship Committees
2002-2003 - American Physical Society Task Force on Countering Terrorism.
2000 - Reviewer, US Department of Defense.
1999 - Reviewer, Department of Energy EPSCoR Program.
1996 - Chair, review panel, National Science Foundation, ILI Program.

Honors

2008 and 2012 Elected Clarence E Denoon Professor of Science.
2004 Who’s Who Among America’s Teachers.
2003 University of Richmond Distinguished Educator Award.

Selected Listing of Refereed Publications

1. O.Hen et al. (CLAS Collaboration), “Momentum sharing in imbalanced Fermi systems”, Science **346**, 614 (2014).
2. M. Moteabbed et al. (CLAS Collaboration), “Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering”, Phys. Rev. **C88**, 025210 (2013).
3. G.P. Gilfoyle, “Few-body physics with CLAS”, Few Body Syst. 50 (2011) 15-22.
4. J. Lachniet, A. Afanasev, H. Arenhövel, W. K. Brooks, G. P. Gilfoyle, D. Higinbotham, S. Jeschonnek, B. Quinn, M. F. Vineyard, *et al.* (The CLAS Collaboration), ’Precise Measurement of the Neutron Magnetic Form Factor G_M^n in the Few-GeV^2 Region’ Phys. Rev. Lett. **102**, 192001 (2009).
5. K.Sh. Egiyan, G.A. Asryan, N.B. Dashyan, N.G. Gevorgyan, J.-M. Laget, K. Griffioen, S. Kuhn, *et al.* (The CLAS Collaboration), ’Study of Exclusive d(e,e’p)n Reaction Mechanism at High Q2’, Phys. Rev. Lett. **98**, 262502 (2007).
6. B. Mecking, *et al.*, (The CLAS Collaboration), ‘The CEBAF Large Acceptance Spectrometer’, Nucl. Instr. and Meth., **503**/3, 513 (2003).
7. G.P.Gilfoyle and J.A.Parmentola, ‘Using Nuclear Materials to Prevent Nuclear Proliferation’, Science and Global Security **9**, 81 (2001).
8. G.P.Gilfoyle, ‘A New Teaching Approach to Quantum Mechanical Tunneling’, Comp. Phys. Comm., **121-122**, 573 (1999).

Selected Invited Presentations

1. “Hall B: User Software Contributions”, 2014 CLAS12 Internal Software Review, Jefferson Lab, Nov 7, 2014.
2. “Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab”, Sixth Workshop on Hadron Physics and Opportunities in the US, Lanzhou, China, July 31, 2014.
3. “Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab”, Workshop on High-Energy Physics in the LHC Era, Valparaiso, Chile, Dec 17, 2013.
4. “MOOC Panel Discussion”, Southeastern Section of the American Physical Society, Bowling Green, KY, Nov 22, 2013.
5. “Hall B: Software Utilization”, 12 GeV Upgrade Software Review, Jefferson Lab, Nov 26, 2013.
6. “Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation”, presented at the University of Virginia Physics Department, January 20, 2012.
7. “CLAS12 Software Readiness Review”, presented at Information Technology for the 12 GeV Era - Internal Review, Jefferson Lab, May 20, 2011.
8. “Precise Measurement of the Neutron Magnetic Form Factor” presented to the Physics Division at Argonne National Laboratory, June 1, 2009.

6 Student Tracking Information

The University of Richmond is a primarily undergraduate institution and the Physics Department has no graduate students. Here we do list the masters student the PI mentored as part of the Richmond/Surrey program described in Section 2.3.

Student	Date Entered Grad School	Date Joined Group	Degree Program	Date Degree Awarded	Advisor
A. Colvill	Feb, 2013	Feb, 2013	Masters	June, 2014	Gilfoyle/Stevenson

7 Current and Pending Support

We have no pending proposals at this time.

By the end of this funding period (5/31/2015) we expect to have the following funds remaining in equipment, travel and undergraduate stipends shown in Table 2. An explanation is below.

	Grant	Item	Amount
1.	Current Grant	Supplies	\$1,500
2.	Current Grant	Travel	\$10,000
3.	Current Grant	Student Stipends	\$2,000
4.	Supplement	Travel	\$6,000

Table 2: Remaining funds

Items 1-2. We have been able to use University funds over the last three years to support travel and some equipment purchases. The PI holds a University of Richmond endowed chair that provides annual funds for professional development. Using these funds for equipment and travel has enabled us to reduce our reliance on the DOE grant. Unfortunately, Gilfoyle's chair has a term limit which will be reached in mid-2015 so those funds will no longer be available.

Item 3. The University supports student summer research with stipends awarded on a competitive basis. My research students have been able to obtain such funding from the University which has allowed us to add students to our group or extend the summer research of others. Last summer one student, Keegan Sherman, was working on the Intel Xeon Phi project (see Section 2.1.1) learning how to write programs that take advantage of the parallelism of the Phi. He was supported for ten weeks with a University stipend. He was making good progress so we extended his summer research for almost five weeks longer using funds from the DOE grant.

Item 4. In the Supplemental grant we received in 2012 to fund the Richmond/Surrey masters student we included funds for travel between Richmond and JLab each week. The idea was to have the masters student attend seminars at Richmond and work with the PI. The nature of the Richmond Physics seminar series has changed significantly in the last two years and it was simply not efficient for the masters student to travel back and forth between JLab and Richmond. It was better for the PI to travel to JLab and work there. That travel is covered by the University's commitment to support routine travel to JLab (see Section 8.1). We have significantly reduced the request for travel funds for the masters student in this proposal.

8 Facilities and Resources

8.1 University of Richmond Resources

The nuclear physics group at the University of Richmond is supported by a computing cluster obtained in 2010 with an NSF MRI grant. See Section 2.1.4 for more details. An array of student workstations is used for software development and non-CPU-intensive tasks all in the Physics Department research area. This cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can take more than a day before submission. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm. The University information technology staff maintains the cluster and provides the Red Hat Enterprise Linux software as part of its licensing agreement.

The University also supports undergraduate summer stipends and student travel. We have had 1-2, university-supported undergraduates working in our laboratory for each of the last three years. All of the student posters cited in Section 2.4 had travel support from either the University, the American Physical Society, or the current DOE contract. The University will support routine faculty travel to JLab at the level of ≈\$3,500 per year for the PI. The University has started a new policy of returning 10% of indirect costs from external grants back to the PI.

8.2 Proximity to Jefferson Lab

Jefferson Lab is 75 miles from the University of Richmond enabling us to maintain frequent contacts with the scientific staff and users. The PI spends about 1 day each week at JLab in addition to time spent on shift, at Collaboration meetings, *etc.* We take students on shift and attend Collaboration meetings at little cost. The University supports routine faculty travel to JLab.

A Confirmation letter from the University of Surrey

UNIVERSITY OF SURREY

Faculty of Engineering and Physical Sciences

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Professor Gerard Gilfoyle
Physics Department
University of Richmond
VA 23173
USA

Monday 15 September 2014

Dear Prof. Gilfoyle

I am writing to express my full support for your DoE research grant application, and also to confirm that we would be delighted to place a Surrey masters MPhys student under your supervision at U. Richmond to work at JLab. The previous placement of a student with you, in 2013, was a great success from our point of view. The student in question graduated with a first class degree thanks, in part, to the work he performed with you in U.Richmond/JLab.

To recapitulate some of the organisational aspects of our placements: They are only for students on our undergraduate masters programmes, which demand a constant high level of achievement to remain on the programme - the condition matching that given by the UK Research Council for PhD bursary funding. At the point of their placement, they will have achieved sufficient credit in the UK system to cash in their degree for an ordinary bachelors degree (BSc), though they do not actually do so, and work directly towards a masters degree.

The MPhys program has run for more than 15 years, and we have been sending students on successful placements around the world, including in the US and Canada, such as Notre Dame University, Yale university, Oak Ridge National Laboratory, and TRIUMF in Vancouver. A measure of success of the quality of the students, and the success of the programme, is that twice (in 2003 and 2006) our students have won the UK's Physics Student of the Year competition - quite a feat given the relatively small size of the Surrey cohort in the UK, competing against students from the likes of Oxford and Cambridge. Surrey students have co-authored more than 50 peer-reviewed research papers over the last decade in the area of nuclear physics alone from their research project work.

For each group of students, their research placement begins in the February, until Christmas time. We would be pleased to offer students for any such year that suits you. Note that the placement students remain enrolled in the University of Surrey, and we assess their performance, but we would expect the student to paid a salary/stipend by the host institution on the basis of their being a funded research student.

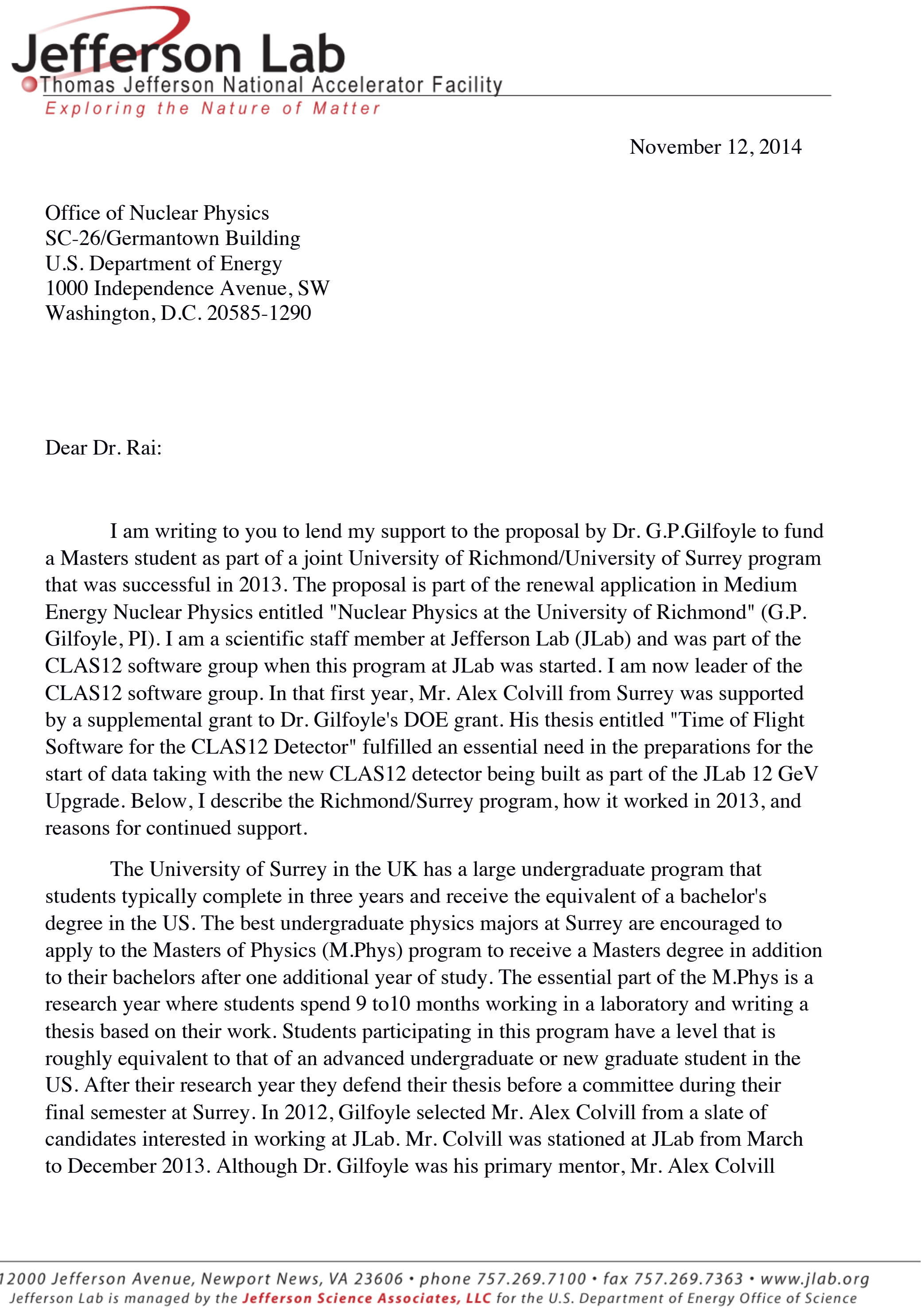
I wish you the best of luck with your DoE proposal, and sincerely hope to be able to send further students to you to benefit from working with you on your project,

yours,

Paul

Dr Paul Stevenson, MPhys Research Year Director, University of Surrey, UK

B Support letter from Jefferson Lab



Jefferson Lab
Thomas Jefferson National Accelerator Facility
Exploring the Nature of Matter

November 12, 2014

Office of Nuclear Physics
SC-26/Germantown Building
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585-1290

Dear Dr. Rai:

I am writing to you to lend my support to the proposal by Dr. G.P.Gilfoyle to fund a Masters student as part of a joint University of Richmond/University of Surrey program that was successful in 2013. The proposal is part of the renewal application in Medium Energy Nuclear Physics entitled "Nuclear Physics at the University of Richmond" (G.P. Gilfoyle, PI). I am a scientific staff member at Jefferson Lab (JLab) and was part of the CLAS12 software group when this program at JLab was started. I am now leader of the CLAS12 software group. In that first year, Mr. Alex Colvill from Surrey was supported by a supplemental grant to Dr. Gilfoyle's DOE grant. His thesis entitled "Time of Flight Software for the CLAS12 Detector" fulfilled an essential need in the preparations for the start of data taking with the new CLAS12 detector being built as part of the JLab 12 GeV Upgrade. Below, I describe the Richmond/Surrey program, how it worked in 2013, and reasons for continued support.

The University of Surrey in the UK has a large undergraduate program that students typically complete in three years and receive the equivalent of a bachelor's degree in the US. The best undergraduate physics majors at Surrey are encouraged to apply to the Masters of Physics (M.Phys) program to receive a Masters degree in addition to their bachelors after one additional year of study. The essential part of the M.Phys is a research year where students spend 9 to10 months working in a laboratory and writing a thesis based on their work. Students participating in this program have a level that is roughly equivalent to that of an advanced undergraduate or new graduate student in the US. After their research year they defend their thesis before a committee during their final semester at Surrey. In 2012, Gilfoyle selected Mr. Alex Colvill from a slate of candidates interested in working at JLab. Mr. Colvill was stationed at JLab from March to December 2013. Although Dr. Gilfoyle was his primary mentor, Mr. Alex Colvill became an integral part of the CLAS12 software group and interacted regularly with me and other members of the group.

Mr. Colvill's M.Phys thesis was on the development of the reconstruction software for the time-of-flight (TOF) sub-systems in CLAS12. It was a significant success that filled an important need in our preparations to complete the JLab 12 GeV upgrade and begin data taking with CLAS12. Mr. Colvill's project contributed to the large software effort involved in the development of the event reconstruction code that will be used to reconstruct and analyze the very high data samples expected from CLAS12 (about 5-10 terabytes each day). There are two time-of-flight (TOF) sub-systems in CLAS12 (forward and central) among the ten major detectors in the baseline equipment. The software environment is unique. A modern, service-based architecture is being used that breaks the overall reconstruction problem into smaller pieces (called services) and manages the interaction of those components to make the code robust and flexible in a demanding, fluid environment.

Mr. Colvill has excellent computational skills, among the best I have seen for students at this point in their careers. He started the project on the forward TOF essentially from scratch. He took an existing service (for the electromagnetic calorimeter) and with little guidance had a version written in Java reading data and generating output in a standalone mode (*i.e.* running without the services for the other sub-systems) in about two weeks. To put in the reconstruction algorithms he started with the code for the previous, pre-Upgrade CLAS detector (written in Fortran). Within two more weeks he had a beta version of the reconstruction service working in standalone mode. He later studied ways to extend, optimize, and test the forward TOF reconstruction and also wrote the code for the central TOF reconstruction service. During this time a stress test was performed on the CLAS12 reconstruction chain. Billions of events were processed and all the existing, sub-system reconstruction services were used to see how the software would fare under realistic operating conditions. Mr. Colvill's TOF services were included in the chain and performed flawlessly. Mr. Colvill received first honors for his thesis, the highest award in the UK.

The Richmond/Surrey program is an excellent source of scientific talent. The students have a strong physics education (better than most US students at liberal arts institutions like Richmond) so they quickly climb the learning curve. The research year lasts long enough to complete a substantial project. The TOF reconstruction software written by Mr. Colvill has become part of the main CLAS12 reconstruction package and his thesis has been published as a CLAS-NOTE (a technical report for the CLAS

Collaboration). It is worth noting that support for capable students like these are an efficient use of resources.

To conclude, I would like to restate my support for Dr. Gilfoyle's proposal to continue supporting a Surrey M.Phys student. This program taps a useful source of scientific talent that makes efficient use of our resources in preparing for the start of data taking in CLAS12. The quality of the program can be judge by the success of the first year of the program at JLab.

Sincerely,

Ziegler.

Dr. Veronique Ziegler

C Budget Justification

YEAR 1 (June 1, 2015 - May 31, 2016)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,500 whichever is smallest.

B.2 One master's student for four months (Feb-May, 2016) at an annual stipend of $27,000 prorated for their time in the program. In the Surrey program the students' research year runs February to December. The dates for this year of the contract are June 1, 2015 - May 31, 2016 so the programs are out of phase. We expect a masters student to arrive by February, 2016 so four months of their research year would be covered in the first year of this contract and the remainder in the second year. There are no tuition costs for this student. This student is classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends.

C Fringe benefit rate is 8% for senior personnel and 26.5% for the Surrey master's student.

E.1 Domestic travel:

1. $1000 - Round trip mileage charge from Newport News, VA to Richmond for the master' student to work with the PI and his undergraduate researchers and attend seminars at Richmond.
2. $2000 - Travel expenses for the master's student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.
4. $7000 - Travel expenses for sabbatical at JLab during the 2015-2016 academic year. Gilfoyle will be on sabbatical at JLab during 2015-2016. To make efficient use of time and money he will spend the week at JLab and return to Richmond on the weekend. He will return to Richmond for one evening a week so there will be two round trips (Richmond - Newport News) and three nights in hotels in Newport News each week. We estimate that commuting costs during the academic year will be about $14,000. There are some existing University funds (about $7,000) that can be used for this purpose leaving $7,000 in travel cost remaining. To calculate the cost for travel to JLab we made the following assumptions: (1) 41 weeks spent at JLab in 2015-2016, (2) hotel rate of $63.32 per night, (3) mileage reimbursement rate of $0.505/mile (University of Richmond rate), (4) two round trips per week (Richmond - Newport News), (5) three nights per week in hotels, and (6) 150 miles per round trip,

   Total = $12,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews including

two overseas. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

G.1 - $1,423 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 23% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.

YEAR 2 (June 1, 2016 - May 31, 2017)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,500 whichever is smallest.

B.2 One master's student for seven months (June-December, 2016) followed by a second student (February-May, 2017) both at an annual stipend of $27,000 prorated for their time in the program. In the Surrey program the students' research year runs February to December. The dates for this contract are June 1, 2016 - May 31, 2017 so the programs are out of phase. We include the support for the full research year in the 2016-2017 grant period and it is split between the end of the first student (2016) and the beginning of the second (2017). There are no tuition costs for this student. This student is classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends.

C Fringe benefit rate is 8% for senior personnel and 26.5% for the Surrey master's student.

E.1 Domestic travel:

1. $1000 - Round trip mileage charge for the master' student to travel to Richmond to work with the PI and his undergraduate researchers and attend seminars at Richmond.
2. $2000 - Travel expenses for the master's student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

   Total = $5,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews including two overseas. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

G.1 - $1,689 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 23% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.

YEAR 3 (June 1, 2017 - May 31, 2018)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,500 whichever is smallest.

B.2 One master's student completing their research year (seven months in 2017) followed by another student for eleven months (Feb-Dec, 2018) at an annual stipend of $27,000 for each. The stipend for the student in 2017 is prorated for the time in the program. In the Surrey program the students' research year runs February to December. The dates for this contract are June 1, 2017 - May 31, 2018 so the programs are out of phase. We include the full year of support for the last student here since Surrey requires the funding be available before matching a student with a research program. There are no tuition costs for this student. This student is classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends.

C Fringe benefit rate is 8% for senior personnel and 26.5% for the master's student.

E.1 Domestic travel:

1. $1000 - Round trip mileage charge for the master' student to travel to Richmond to work with the PI and his undergraduate researchers and attend seminars at Richmond.
2. $2000 - Travel expenses for the master's student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

Total = $5,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given 9 invited talks at conferences, universities, and JLab reviews including two overseas. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

G.1 - $1,955 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 23% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.