Medium Energy Nuclear Physics Research at the University of Richmond

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Grant Contract Number DE-FG02-96ER40980
Grant Period: June 1, 2021 - May 31, 2024

Office of Nuclear Physics: Medium Energy Nuclear Physics Program
Program Manager: Dr. Gulshan Rai

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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 use the Thomas Jefferson National Accelerator Facility (JLab) to measure the charge and current distributions of the neutron. In experiment E12-07-104 (spokesperson: Gilfoyle) we have collected data to measure the neutron magnetic form factor G_M^n at high Q^2. We are part of the group working to reconstruct, analyze, and simulate these data from the CLAS12 detector. We have also made a preliminary measurement of the CLAS12 neutron detection efficiency needed to precisely determine G_M^n from the recent deuterium runs. We have continued our work to develop and enhance the CLAS12 Common Tools.

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) using the CLAS12 detector in Hall B. Dr. G.P. Gilfoyle is the principle investigator (PI) and full member of the CLAS Collaboration which operates CLAS12. The 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 and the Surrey masters students. Two Surrey students (Michael Armstrong and Adrian Saina) were supported during the current, 3-year grant period.

Title	Label
Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium (Gilfoyle: spokesperson and contact person)	E12-07-104
CLAS12 Software	
Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)	E12-06-117
Precision measurement of the neutron magnetic form factor up to $Q^2 = 18\ (GeV/c)^2$ by the ratio method	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 review (2017). Our major focus now is on analysis of CLAS12 data collected recently to measure G_M^n, the magnetic form factor of the neutron. We are part of a broad program at JLab to measure the elastic, electromagnetic form factors consisting of seven experiments including two to measure G_M^n. The PI (Gilfoyle) is spokesperson and contact person for the CLAS12 G_M^n experiment (JLab Experiment E12-07-104) and is a co-spokesperson on the Hall A G_M^n measurement (E12-09-019). Both experiments use methods pioneered in Hall B with the previous detector CLAS6 [1]. The PI is one of the lead authors on that work.

Our measurement uses the ratio of $e-n$ to $e-p$ scattering from a deuterium target to extract G_M^n and relies on data from electron scattering on a hydrogen target to determine the neutron detection efficiency. More details are below. We have completed the first round of deuterium runs as part of Run Group B in Hall B and accumulated 39 PAC days out of the 90 PAC days approved for the Run Group over three time periods. We collected 43 billion triggers at three beam energies (10.2, 10.4, and 10.6 GeV). Cooking of one data set (spring, 2019) is complete and calibrations are done for other two run periods (fall, 2019 and winter, 2020). The PI was run coordinator for the spring, 2019 and winter, 2020 run periods (total of 18 days). The G_M^n analysis is moving forward with the development of event selection criteria for the $e-n$ and $e-p$ events used in the ratio. Here, we have collaborated with Dr. B.Raue from Florida International University (FIU) and his doctoral student Ms. L. Baashen. The G_M^n analysis will be her thesis.

An essential quantity in our analysis is the neutron detection efficiency (NDE) to provide an accurate measure of the number of $e-n$ events. We use a hydrogen target and the $^1\mathrm{H(e, e'\pi^+)n}$ reaction as a source of tagged neutrons and have extracted the NDE from Run Group A data. We have obtained preliminary results that are the topic of a contributed talk at the fall, 2020 APS Division of Nuclear Physics (DNP) meeting [2]. The precision of our results at high neutron momentum (corresponding to high Q^2) is encouraging.

We also continued our commitment to develop software for the simulation, reconstruction, and analysis of CLAS12 data. During this grant period we used codes written by two former Richmond undergraduates (K.Sherman and A.Balsamo) to extract the G_M^n ratio from the deuterium data and to determine the NDE from the hydrogen data. Both codes have been used successfully in the current G_M^n analysis [3, 4, 5]. We also updated and expanded reconstruction unit tests used to ensure consistent results from the code [6, 7] and determined the resolution of the reconstruction software in simulation [8]. These last two projects were done by two Surrey masters students M. Armstrong and A. Saina. Mr.Armstrong's project is the topic of a CLAS12 NOTE [6] and Mr.Saina's work will also be published as a CLAS12 NOTE when he completes his research year. We also completed our contribution to the SVT alignment.

We now summarize our Plan of Work. We will continue the collaboration with FIU and complete the analysis of the G_M^n data and contribute to the software effort for CLAS12. The PI will be on sabbatical during the 2022-2023 academic year and is making arrangements for spending the sabbatical at JLab. This will be in the later stages of the G_M^n analysis so he will be well-positioned to contribute to that work. We have developed simulations to study ways to optimize the analysis, *e.g.* reduce neutral backgrounds and increase the signal size. We have just begun to study methods for *in situ* monitoring of the NDE using tagged neutrons from reactions like $^2\mathrm{H}(e, e'np)$ and others. We will continue our contributions to the CLAS12 software development coordinating our work with Dr. V.Ziegler who is the lead developer for the CLAS12 reconstruction code.

We request funds to support masters students in a cooperative program between the University of Richmond and the University of Surrey in the UK (see Section 2.3). Undergraduates from Surrey are selectively admitted to the masters program and required to spend ten months engaged in research. These students' work is matched to their interests, the program here, and the activities in our collaboration at JLab. The addition of these students (one per year for two of the three years of the grant period) raises our scientific productivity. The Surrey program has been successful in the nuclear structure community at Yale, Kentucky, Florida State, Notre Dame, LBL, and Richmond. Those programs benefited from the Surrey students and many 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. We now discuss our work to analyze recently collected data using the CLAS12 detector and continued preparations for future experiments. 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 measure and identify the reaction products [9]. 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 the 12 GeV era has grown. We remain committed to these goals.[10, 11, 12, 13]

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 (see Section 2.1) [14], and forms a central part of the physics programs at JLab [15, 16, 17, 18]. 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 includes seven experiments approved for running after the 12 GeV Upgrade at JLab [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 CLAS12 [19]. The experiment has an A$^-$ rating from the Program Advisory Committee (PAC) and was awarded 30 days of beamtime in the first five years running of CLAS12 [20]. A large portion of our work now is analyzing the recently completed deuterium runs to extract G_M^n and preparations for further CLAS12 operations. We are also members of the collaboration to measure G_M^n in Hall A (E12-09-019).

We first outline the steps of the the measurement of the neutron magnetic form factor followed by a summary of recent experimental activity. To extract G_M^n we form the ratio R of $e-n$ to $e-p$ events in quasielastic scattering (QE) from deuterium. This quantity R depends on all four elastic, electromagnetic form factors (EEFFs): G_M^n, G_E^n, G_M^p, and G_E^p. The proton EEFFs are known to higher precision than the neutron ones so their contribution to the G_M^n systematic uncertainty will be limited. The neutron electric form factor G_E^n is not well known at high Q^2, but it's contribution to R is small and parameterizations are available that account for its high-Q^2 behavior. More details on the method are in Section 2.2.1.

We now discuss the status of the G_M^n analysis of the deuterium data. The data were collected as part of the CLAS Collaboration's Run Group B (RGB). The run statistics for the three separate experimental runs are listed in Table 2. Nearly forty PAC days of running generated more than 43 billion triggers constituting about 43% of total PAC days approved for RGB. The PI (Gilfoyle) served as Run Coordinator for RGB during the spring, 2019 run (seven days) and during the winter, 2020 run (11 days) which came immediately after the JLab winter shutdown.

With the arrival of the first CLAS12 deuterium data the PI formed a collaboration with Dr. B. Raue, a CLAS Collaboration colleague at Florida International University (FIU) and his doctoral student Ms. L. Baashen. The G_M^n analysis is Ms. Baashen's PhD thesis. The group typically meets 1-2 times per week and pre-COVID Gilfoyle spent one day each week at JLab. Since March, 2020 the group has maintained these regular meetings remotely.

	Spring, 2019	Fall, 2019	Winter, 2020	Sum
Beam [GeV]	10.2, 10.6	10.4	10.4	
PAC days	21.7	6.7	10.5	38.9 (43%)
Triggers [B]	21.4	9	12.9	43.3
Charge [mC]	79.6	21.7	35.2	136.5
DAQ [kHz]	14	24	19	

Table 2: Run Group B data collection properties and statistics.

Analysis ("cooking") of the RGB data is underway. As of October, 2020 cooking is complete (Pass 1) for the spring, 2019 run and Pass 1 for the fall, 2019 run will occur in the next month. Calibrations for the winter 2020 are in process (Pass 0).

Some preliminary results from our group's analysis are shown in Figure 1. The left-hand panel shows W^2 plotted versus θ_{pq} for the ^{2}H(e, e$'$p) reaction. The angle θ_{pq} is between the exchanged, virtual photon γ^* and the ejected proton. We expect the quasi-elastic production to be at small θ_{pq} while the inelastic background will occur at higher W^2 and larger θ_{pq} for both protons and neutrons. The proton results in the left-hand panel of Figure 1 display that property - the quasielastic group

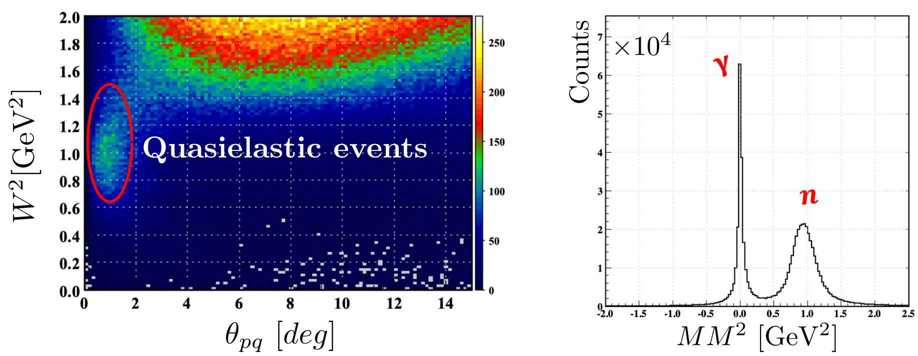

Figure 1: Preliminary results for RGB G_M^n analysis of the ^{2}H(e, e$'$p) reaction showing W^2 versus θ_{pq}, the angle between the virtual photon and the ejected proton (left panel). The right panel shows the missing mass squared for the same reaction before selecting the quasi-elastic events.

is clearly separated from the inelastic background. The right hand panel shows the square of the missing mass for neutral particles in our data sample. There is a clear separation between the photons and neutrons. Optimizing the event selection is ongoing.

A key step in measuring G_M^n with the ratio method is to also measure the neutron detection efficiency (NDE) to determine precisely the number of $e - n$ events in R. We use the $^1\mathrm{H}(e, e'\pi^+ n)$ reaction on a hydrogen target as a source of tagged neutrons to measure NDE in the CLAS12 calorimeters [21]. We select $^1\mathrm{H}(e, e'\pi^+)n$ events with a missing mass cut and other kinematic constraints and predict the location of the neutron in the the CLAS12 calorimeters. These events form the denominator in the NDE. We reject events if the predicted neutron path misses the CLAS12 fiducial volume. We then search for a neutron hit close to the expected location. If a neutron is detected it goes into the numerator of the efficiency.

We are extracting the NDE from hydrogen data collected during Run Group A (RGA) running. Run statistics for the three separate runs are listed in Table 3. Over sixty PAC days of running and 285 mC of charge collected constitutes over 40% of total beam-time approved for RGA. The

	Spring, 2018	Fall, 2018	Spring, 2019	Sum
Beam [GeV]	6.4, 10.6	10.6	10.2	
PAC days	21.7	30	10	61.7
Charge [mC]	126	99	60	285 (46%)

Table 3: Run Group A data collection properties and statistics.

analysis of the RGA data is far along and we have exploited that to begin extracting the neutron detection efficiency. Preliminary results are shown in Figure 2. In the left-hand panel we show the

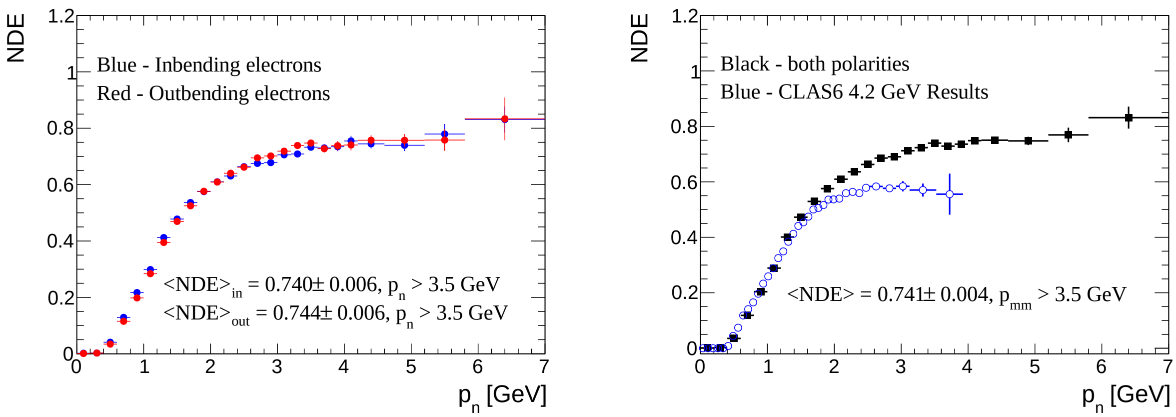

Figure 2: Preliminary results for the neutron detection efficiency from the ^{1}H(e, e$'\pi^+$n) reaction as a function of neutron momentum p_n. Data are from Run Group A.

NDE extracted for opposite polarities of the CLAS12 torus magnet. The NDE rises rapidly in the range 0.5 GeV/c $< p_n <$ 3 GeV and levels off at higher Q^2. There are differences between the two measurements at low missing momenta where the NDE is changing rapidly. At $p_n \gtrsim$ 3.2 GeV/c the NDE for each polarity reaches at plateau at NDE $\approx$ 0.74. In the region of the plateau the average values for the plateau for the two torus polarities agree within less than 1%. In the right-hand panel we show the NDE for the combined torus magnet polarities (black, filled, squares). As expected we see improved statistical precision at high p_n. For comparison we show results from the previous CLAS6 detector in Hall B. The current CLAS12 calorimeters include the refurbished CLAS6 calorimeter used to measure the blue points (open circles) in the right-hand panel. The two measurements are consistent with each other in the low-p_n region where the NDE changes rapidly. With the construction of CLAS12 a new calorimeter (Pre-shower calorimeter or PCAL) was added. This addition explains the higher plateau for the CLAS12 detector because there is more material for the neutrons to pass through and a greater chance for them to interact and produce a signal. Finally, it is worth noting these results are from just the fall, 2018 RGA run so the amount of data in the final NDE sample will more than double.

Simulation of the CLAS12 detector and the physics processes is an essential tool to understand the CLAS12 response, to validate our own codes and algorithms, and to explore the physics more deeply. We have developed a full, end-to-end simulation for the G_M^n project [5, 22, 23]. These projects include development of an event generator for quasielastic events [24] and in the last 18 months new tools for simulating the inelastic background. We have begun to use a variation of the Pythia event generator [25] that includes nuclear effects. The goal is to study the inelastic background under the neutron peak to optimize the extraction of the yield from the $e-n$ and $e-p$ events. Our initial results are encouraging.

In the fall of 2020, the JLab Program Advisory Committee (PAC) performed a jeopardy review of Run Group B. In a jeopardy review the PAC evaluates the continued relevance of the experiments in the run group and can change the amount of remaining beam time, the scientific rating, *etc.* PAC48 (fall, 2020) recommended that Run Group B remain active, keep the full amount of the original, approved beam time, and maintained the scientific rating at A. A related report by the Technical Advisory Committee to the PAC assessed the theoretical goals of the run group. It was supportive of the Run Group B physics program and noted in the section discussing the G_M^n experiment that "Theoretical support for these measurements remains very strong." [18].

2.1.2 CLAS12 Software Development

The University of Richmond group continues to develop software to support continuing CLAS12 operations. Since 2017 Richmond undergraduates and Surrey students have written codes to extract G_M^n, measure NDE, monitor analysis run-by-run, and a variety of other tasks.[2, 5, 7, 8, 22, 26]. Here we describe two projects from the current grant period from the Surrey students that are supported by this DOE grant.

Code testing and validation are essential for developing robust, accurate, high-performance software. The goal is to catch mistakes/bugs introduced as the programs evolve and to monitor changes in performance. This goal is especially important in large collaborations where many people are working on the software so it changes at a rapid pace. During the nightly software builds, unit tests are run on the subsystems to test their performance. The unit tests are part of an array of automatic tests the "have proven invaluable in overseeing software development" [27].

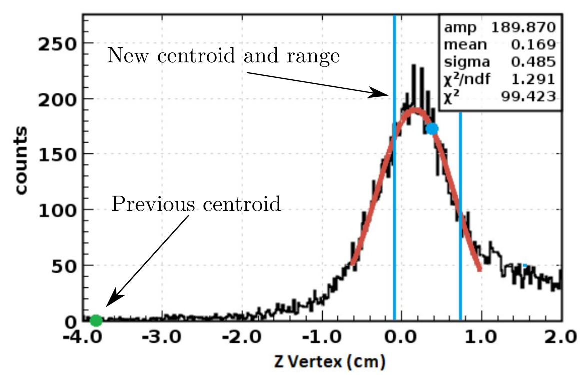

Figure 3: Distribution of the z-component of the track vertex for simulated electrons in CLAS12. Previous test point shown in green. Current test point and range shown in blue.

Mr. M.Armstrong, a Surrey masters student working with the PI and JLab staff scientist Dr.V.Ziegler updated and expanded a unit test on the CLAS12 drift chambers to test changes to the CLAS12 reconstruction code. The unit test here is part of the Drift Chamber (DC) subsystem. A previous unit test consistently produced false positives so its warning had become unusable. The source of this failure was identified and the test modified for use with the latest version of the CLAS12 Common Tools. An example is shown in Figure 3. Tracks were simulated with the CLAS12 standard simulation *gemc* and reconstructed with the CLAS Collaboration's Common Tools package. In Figure 3 simulated data have been reconstructed to extract v_z, the z-component of the track vertex. The red curve is a fit to the region around the peak and the centroid and range of the unit test are shown by the blue dot and vertical lines. The previous test event is shown by the green dot at $v_z = -3.84$ cm, more than 8σ from the centroid of the peak. The reconstruction code had evolved so the old unit test returned a v_z far from the expected value of zero. This code is now part of the regular CLAS12 software distribution [6].

Mr. A.Saina, another Surrey masters student is now completing a study of the reconstruction resolution of the CLAS12 software also working with Dr. Ziegler. The resolution here is measured by swimming two simulated tracks through the CLAS12 Forward Detector. One track uses the known/generated vertex and initial 3-momentum from the event generator that was the input to the simulation. The second track uses the reconstructed vertex and momentum produced by the reconstruction code itself. Differences between these two tracks at different detector subsystems are used to fill histograms and the width of the histogram is a measure of the reconstruction resolution. The effects of particle energy, particle type, torus field polarity, sector dependence, and geometry were studied using two recent versions of the CLAS12, physics-based simulation code *gemc*.

In Figure 4 we show the change of the resolution between *gemc* version 4.4.0 (yellow points) and 4.3.2 (blue points) for $\Delta\theta$ and $\Delta\phi$ at fixed z. In upgrading *gemc* the generation of the subsystem signals was made more realistic. The z-component here is in a special sector coordinate system where x and y lie in the plane of the CLAS12 drift chambers, TOF panels, and calorimeters and the z-axis is perpendicular to those planes. There is about a 50% increase in the widths of the distributions at fixed z in the more recent version of *gemc* and the results are closer to what we observe. This work will be the topic of a CLAS12-NOTE now in preparation.

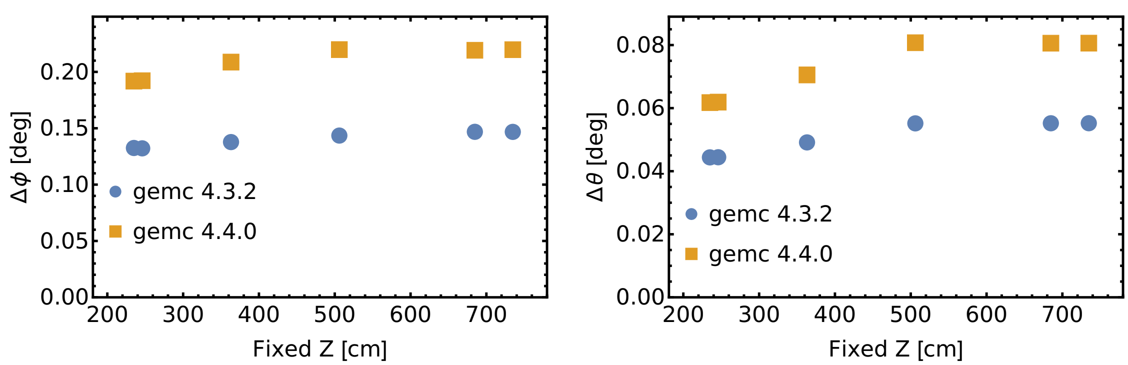

Figure 4: Fit results for the widths of the $\Delta\phi$ (left) and $\Delta\theta$ (right) distributions for *gemc* version 4.4.0 (yellow points) and 4.3.2 (blue points).

2.1.3 SVT Alignment

During the first half of the current grant period, the PI continued working on the track-based alignment of the Silicon Vertex Tracker (SVT) in the Central Detector. This project built on the work of a Surrey Masters student, Peter Davies, who developed and validated the SVT geometry software and made it consistent with the design drawing of the SVT [28]. These tools are still in use. With the start of Run Group B and the arrival of deuterium data, the demands of the G_M^n project prevented the PI from continuing. A description of the SVT work is in Ref. [29].

2.1.4 Summary

With the arrival of the first deuterium date in Run Group B, the Richmond group has begun the analysis of the G_M^n experiment with collaborators from Florida International University. The preliminary results on the neutron detection efficiency are encouraging. We continue to optimize the selection of $e-n$ and $e-p$ events that go into the ratio. Our University of Richmond undergraduates and University of Surrey masters students are contributing to the software enterprise in the CLAS Collaboration in general and specifically for the G_M^n analysis. Their work is described in two CLAS12 NOTES and presentations at the annual DNP meeting [2, 5, 7, 8, 22, 26]. The geometry and alignment of the SVT project is far along.

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 program. Gilfoyle will spend his sabbatical during 2022-2023 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. There are four experimental halls (Halls A-D) that can collect data simultaneously and provide complementary capabilities (see left-hand panel in Figure 5). CLAS12 in Hall B is a large particle detector with

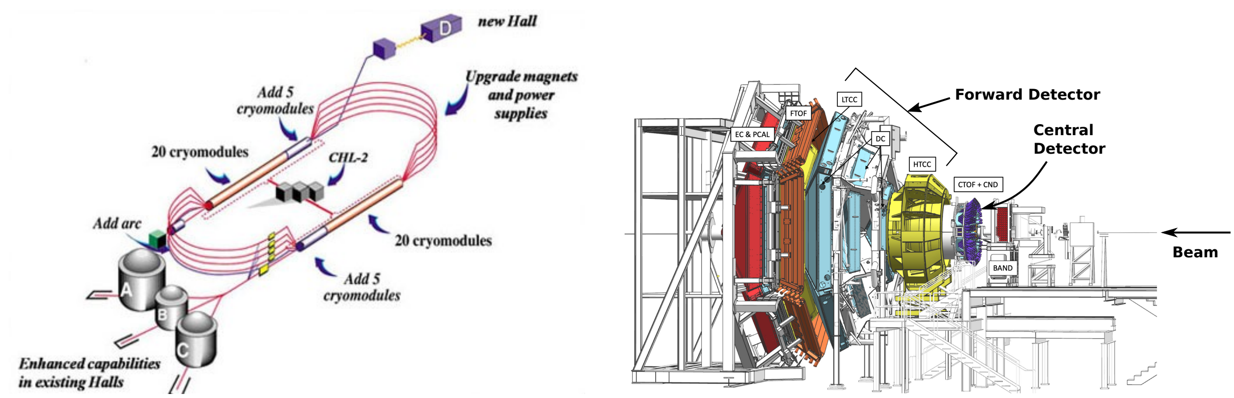

Figure 5: CEBAF layout (left) and CLAS12 design drawing (right).

a toroidal, multi-gap magnetic spectrometer with large solid angle coverage at forward angles (the Forward Detector) and a solenoid centered on the target for large angles (the Central Detector). See the right-hand panel in Figure 5. There are over 100,000 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 [30] to measure charged particle trajectories, Cerenkov detectors [31] to identify electrons, pions, and kaons, scintillators [32] for time-of-flight measurements, and electromagnetic calorimeters [33]. The six segments are instrumented individually to form six independent spectrometers. The Central Detector is built around a solenoid magnet with silicon and micromegas trackers, a time-of-flight system, and a central neutron detector. The CLAS Collaboration operates and manages CLAS12 with support from the US Department of Energy. The Richmond group has been part of the CLAS Collaboration since its inception.

Our focus for the next three years is (1) on the analysis of data already collected in Run Groups A and B in Hall B to measure G_M^n, (2) continued development of software to support CLAS12 reconstruction and analysis, (3) participate in the Hall A G_M^n measurement as resources and time permit, (4) participate in the JLab experiment E12-06-117 *Quark Propagation and Hadron Formation*, and (5) other activities.

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 non-perturbative region (see Sect 2.1 of the NSAC Long-Range Plan) [14]. 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 distribution of magnetization within the neutron. It is central to our understanding of nucleon structure [14, 15, 16, 17, 34]. 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 includes seven experiments approved for running [17, 35].

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 [20]. 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 continue the analysis of data from Run Groups A and B in Hall B to extract a precision measurement of the neutron magnetic form factor. We are part of a collaboration with Dr. Brian Raue and his doctoral student Ms. Lamya Baashen at Florida International University (FIU). Our progress so far is described in Section 2.1.1 and more details of the method are below.

Here we present some background to the study of elastic electromagnetic form factors (EEFFs) and motivate their measurement. The most general form of the hadronic current for a nucleon is

$$\mathcal{J}^\mu = ie\overline{\nu}(p')\left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}k_j F_2(Q^2)\right]\nu(p)\ check\ \nu\ q\sigma \tag{1}$$

where M is the nucleon mass, k_j with $j = p, n$ is the anomalous magnetic moment in units of the nuclear magneton, the ν and $\overline{\nu}$ are the Dirac spinors, q_ν is the momentum transfer, and $\mu_N = e\hbar/(2M_p)$[36]. The Dirac and Pauli form factors are $F_1(Q^2)$ and $F_2(Q^2)$ respectively. These are routinely written in terms of Sachs form factors

$$G_E^{(p,n)} = F_1^{(p,n)} - \tau F_2^{(p,n)} \text{ and } G_M^{(p,n)} = F_1^{(p,n)} + F_2^{(p,n)} \tag{2}$$

where $\tau = Q^2/4M^2$.

Measuring G_M^n and other elastic electromagnetic form factors (EEFFs) will decisively impact our understanding of the nucleon in the 12-GeV era. By measuring all four nucleon EEFF's and invoking charge symmetry the quark Dirac and Pauli form factors can be extracted in the following way [37, 38].

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \qquad \text{and} \qquad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)} \tag{3}$$

The result of this flavor decomposition is shown in the left-hand panel of Figure 6 [37]. There are large differences between the u- and d-quark distributions both in size and shape. The u-quark form factors in Figure 6 are scaled by Q^4 and rise steadily across the full range while the d-quark form factors saturate at around $Q^2 = 1.4$ GeV^2. In addition, the Q^2 dependence of the form factor ratio F_2/F_1 for the nucleons is predicted by non-perturbative QCD to follow a $1/Q^2$ form (Figure 1 in Reference [37]). This feature differs sharply from the results for the individual quarks in Reference [37]. These data have opened a new window into the nucleus.

One example of that opening is shown in the right-hand panel of Figure 6. AdS/QCD is a program to describe quantum chromodynamics (QCD) in terms of a dual gravitational theory (anti-de Sitter or AdS space) which has sparked considerable work. It holds the promise of an analytical solution to QCD in the non-perturbative regime. To obtain discrete hadron masses in the AdS space one must break the appropriate symmetry. Two schemes which are analytically tractable are the hard-wall model where the AdS space has a sharp cutoff and boundary conditions

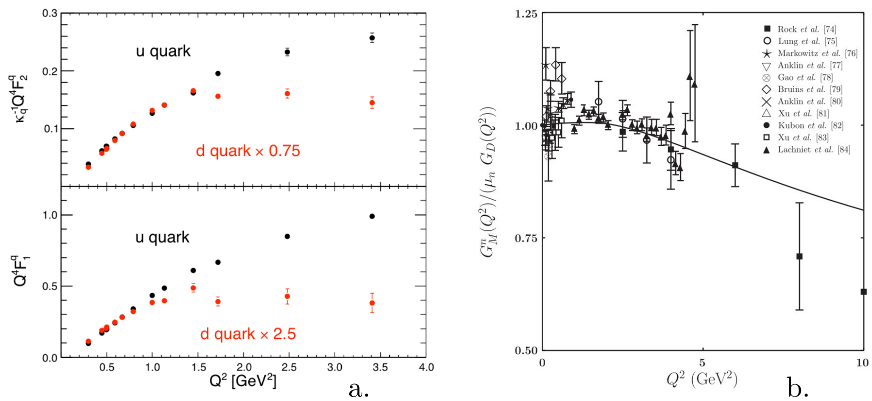

Figure 6: Flavor decomposition of the nucleon elastic form factors showing (a) the Q^2 behavior of the Dirac and Pauli form factors for the $u-$ and $d-$quarks [37] and (b) a soft-walled AdS/QCD calculation [39]. The form factors in the left-hand panel are multiplied by Q^4 to show their properties more clearly while in the right-hand panel G_M^n is divided by the dipole form factor μG_D.

are imposed and a soft-wall approach where additional interactions are added to suppress long distance propagation [40]. In Ref. [39], Gutsche *et al.* include contributions to the action that bring the momentum dependence of the form factors closer to the measured ones. Their results for G_M^n are shown in the right-hand panel of Figure 6. There is good agreement with the existing, high-precision G_M^n data out to $Q^2 \approx 4.5$ GeV^2.

The elastic form factors for both the proton and neutron are an important, early test case of the accuracy of lattice QCD calculations. With all four of them, one can extract the isovector combination of the form factors [41] which are easier to calculate on the lattice because they lack disconnected contributions [20]. Lattice QCD calculations of the EEFFs are still restricted to the few-GeV^2 range, but over the next decade these calculations will reach higher Q^2 [42, 43, 44, 45]. We also expect to obtain a new, unprecedented tomographic view of the interior of the nucleon through measurement of generalized patron distributions (GPDs). The integrals shown in Eq. 4

$$\int_{-1}^{1} dx H^q(x,\zeta,Q^2) = F_1^q(Q^2) \text{ and } \int_{-1}^{1} dx E^q(x,\zeta,Q^2) = F_2^q(Q^2) \quad (4)$$

show the integral over Bjorken x returns the Dirac and Pauli form factors. The EEFFs are a limiting case of the GPDs and provide a constraint on GPD models [46, 47]. There is a great opportunity here for discovery.

The potential physics reach of the G_M^n measurement is shown in Fig 7. 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 and were determined using the parameterization of Alberico *et al.* [48]. 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 $Q^2 \approx 10$ (GeV/c)^2, more than doubling the range of the existing high-precision measurements. The anticipated Hall A results are the blue, open squares and will extend the high-statistics measurement out to $Q^2 = 13.5$ GeV^2 though in larger steps. The theory curves in Fig 7 represent a range of approaches to the problem. The AdS/QCD calculation by Gutsche *et al.* is shown (short-dashed curve) along with calculations using the light-front quark model (LFQM) to build a quark-diquark model of the nucleon with an explicit pion cloud (dot-dashed curve from Miller *et al.* [49]) and a calculation based on the

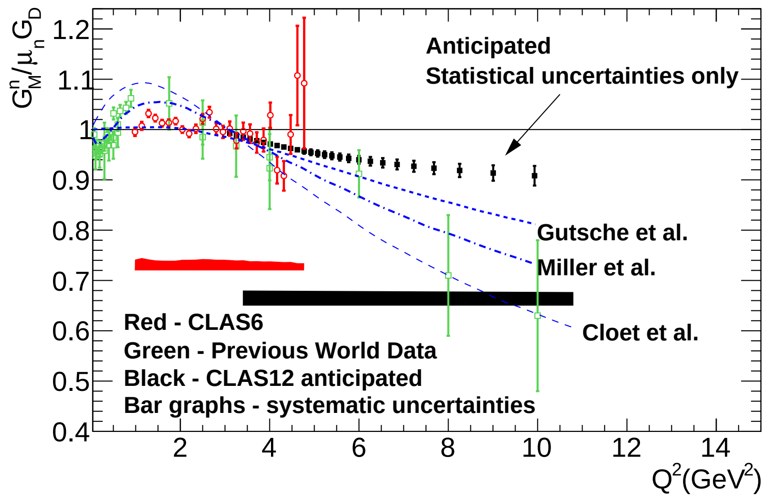

Figure 7: Results for $G_M^n/(\mu_n G_D)$ from CLAS6 (red), previous data (green) [51, 52, 53, 54, 55, 56, 57], theoretical calculations, and expected data from CLAS12 (black) are shown.

Dyson-Schwinger equation (long-dashed curve from Cloet *et al.* [50]). These calculations produce diverging predictions in the Q^2 region we are probing with the CLAS12 G_M^n measurement. All the calculations diverge for $Q^2 > 5$ (GeV/c)^2; above the range of nearly all the existing, high-precision data. The JLab G_M^n campaign will explore this region.

We now describe in more detail our method to determine G_M^n. We start with 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 in the one-photon exchange approximation as [58]

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left[\frac{{G_E^n}^2 + \frac{\tau}{\epsilon}{G_M^n}^2}{1+\tau}\right] = \sigma_{Mott}\left[\frac{{G_E^n}^2 + \tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2 \tan^2\left(\frac{\theta}{2}\right)\right] \quad (5)$$

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

$$R = \frac{\frac{d\sigma}{d\Omega}\left[{}^2\text{H}(e,e'n)p\right]_{QE}}{\frac{d\sigma}{d\Omega}\left[{}^2\text{H}(e,e'p)n\right]_{QE}} = a(E,Q^2)\frac{\sigma^n_{Mott}\frac{{G_E^n}^2+(\tau_n/\epsilon_n){G_M^n}^2}{1+\tau_n}}{\sigma^p_{Mott}\frac{{G_E^p}^2+(\tau_p/\epsilon_p){G_M^p}^2}{1+\tau_p}} \quad (6)$$

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 [59]. This equation can be solved for G_M^n to obtain

$$G_M^n = \sqrt{\left\{\left(\frac{R}{a(E,Q^2)}\right)\left(\frac{\sigma^p_{Mott}}{\sigma^n_{Mott}}\right)\left(\frac{1+\tau_n}{1+\tau_p}\right)\left(G^2_{E,p} + \frac{\tau_p}{\epsilon_p}G^2_{m,p}\right) - G^2_{E,n}\right\}\left(\frac{\epsilon_n}{\tau_n}\right)} \quad (7)$$

Equation 7 requires knowledge of the proton form factors G_M^p and G_E^p. The denominator in Equation 6 is essentially the measured proton cross section which is known to high precision so it will have limited impact on the anticipated systematic uncertainties for G_M^n. Equation 7 also uses the neutron electric form factor G_E^n, but it is smaller than G_M^n by a factor of six or more and its contribution is kinematically suppressed at large Q^2. It has limited effect on extracting G_M^n here. By taking the ratio R we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction and trigger inefficiencies, the deuteron wave function, and radiative corrections [1, 19, 60, 61]. We also measure the $e-n$ and $e-p$ events in a single CLAS12 measurement at the same time further reducing systematic uncertainties.

To start extracting R we search for $^2\text{H}(e,e'n)$ and $^2\text{H}(e,e'p)$ events with no other particles charged or neutral. In quasi-elastic (QE) scattering the other nucleon will have little energy. For each of these candidate events found we perform acceptance matching. We assume the detected nucleon is scattered elastically and predict/swim the trajectory of BOTH a scattered proton and a neutron through CLAS12 to see if they are both within the CLAS12 acceptance. If both nucleons are expected to strike CLAS12 we accept the event. This procedure ensures the sample of events has the same solid angle for both neutrons and protons.

Next, 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]. In Figure 8 we show how this angle is defined. In the left-hand panel of Figure 1 in Section 2.1.1 we show a preliminary plot of the recoil mass squared W^2 versus θ_{pq}. The events highlighted in the red ellipse are the QE ones. We see a clear separation between these events and the inelastic background. This technique of applying a kinematic cut to select QE events can be applied equally well to both proton and neutron events - reducing biases in the analysis by using the same method for both nucleons. We then apply a cut on W^2 to remove additional inelastic events from the sample.

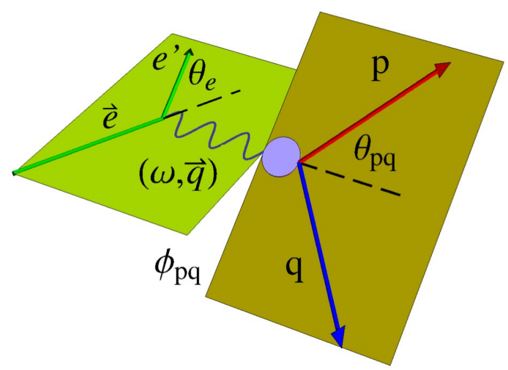

Figure 8: The definition of θ_{pq} is the angle between the 3-momentum transfer $\vec{q}$ and the 3-momentum of the ejected nucleon.

The method described here does require precise knowledge of the neutron detection efficiency (NDE). Comparison of past measurements at different laboratories reveals considerable tension among those experiments possibly due to variations in detector performance and efficiency [62]. To measure the neutron detection efficiency we use the $^1\text{H}(e,e'\pi^+n)$ reaction on a hydrogen target from Run Group A (RGA) data. This reaction is a source of tagged neutrons which can be detected in two, overlapping measurements with both the electromagnetic calorimeter (PCAL/EC) and the forward time-of-flight (FTOF) system - providing a powerful consistency check on the measurements. Run Group A has collected abundant hydrogen data under different run conditions and different times so we can study variations in the NDE and determine its systematic uncertainty.

To measure the NDE we start with the $^1\text{H}(e,e'\pi^+X_n)$ reaction where X_n is a single neutral particle. We infer the mass of the unobserved neutron from the measured electron and pion kinematics and predict/swim the candidate neutron path through CLAS12. This track is required to lie within the CLAS12 acceptance. We call this the expected track. We then search this event for neutral hits in the PCAL/EC or FTOF and calculate the distance ΔR between the intersection point of the expected track with the front face of the detector and the intersection point of each measured track with the front face of the detector. We select the hit with the smallest ΔR and call it the measured track. We then calculate the direction cosines of the expected and measured neutron momentum vectors with respect to the beamline and take the difference between these two tracks. Figure 9 shows the difference is strongly peaked around zero. We require these residuals to be within ±0.1 of each other. Finally, we add additional cuts in the M^2 versus p_n plane to eliminate overlaps with photon events. Our preliminary results for the NDE using the PCAL/EC system from the fall, 2018 RGA run are shown in Figure 2 in Section 2.1.1. The uncertainty in the plateau at high neutron momentum p_n is about 0.5% which is within the proposed upper bound for the NDE contribution to the systematic uncertainty [19]. This region $p_n >$ 3.5 GeV/c corresponds to where the $Q^2 > 5$ GeV^2 which exceeds the reach of the CLAS6 measurement and is new territory for high-precision measurements of G_M^n.

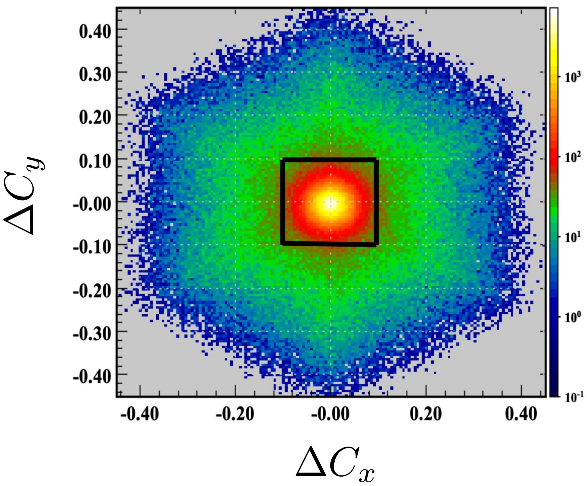

Figure 9: Differences in direction cosines between the expected and measured momenta of the tagged neutron in the ECAL.

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 elastic scattering, and calculating the trajectory for the proton. If the proton is expected to strike the active area of the detector, we continue with the analysis, otherwise the event is rejected [1, 5, 23, 60]. The methods described here were successful in our previous analysis of the CLAS6 E5 data [1].

There are corrections to apply to the $e - n/e - p$ ratio R. The Fermi motion can alter the trajectory of the nucleons and literally knock neutrons or protons out of the CLAS12 acceptance. Recall we determine the nucleon trajectory from the electron information and ignore final-state interactions (FSI). If the direction of the ejected nucleon is altered by FSI that nucleon might completely miss the CLAS12 acceptance and would not contribute to the ratio R. Note that there is no corresponding Fermi induced migration of nucleons into the CLAS12 acceptance because those events would be rejected since their predicted trajectory takes them outside the acceptance. Our experience with the CLAS6 G_M^n shows the Fermi motion can have a significant impact on the ratio R at $Q^2 < 2$ GeV^2, but the effect declines at large Q^2. Radiative corrections can also effect R. Calculating the effect is standard practice in the CLAS Collaboration and we will follow that method. Our past work on the CLAS6 measurement showed the effect is of the order of 1-1.5% depending on the ϕ_{pq} angle. The last topic is nuclear corrections. This factor is $a(Q^2)$ in Eq. 6. A variety of approaches can be used to calculate this factor. We found in the CLAS6 measurement the calculations approached unity at increasing Q^2 so we expect a similar effect here.

We will also consider possible ways to perform *in situ* measurements of the NDE using the deuterium target in RGB. Depending on the neutron momentum range and the statistical precision we could use other reactions to measure NDE, provide a consistency check on the hydrogen NDE measured with the RGA data, and perhaps improve the precision of the measurement. There are several potential reactions that could be used. Tagged neutrons could be generated with the ^{2}H$(e, e'\pi^+)nn$ reaction [63]. Electrons would scatter off the proton in deuterium to produce π^+'s and we would follow a procedure similar to the one described above for the hydrogen target in RGA. The Fermi motion of the proton would likely increase any overlap of the quasi-elastic events with the inelastic background requiring a program of simulations to test the idea. The result of a very early study of this reaction is shown in Figure 10. It shows the square of the missing mass with a clear peak at the neutron mass. More study is required to determine the viability of this approach. The quasielastic ^{2}H$(e, e'pn)$ reaction could be used. Here we would detect the final-state electron and proton and predict the location in CLAS12 of the neutron. We then look for that neutron in CLAS12 in a narrow, angular cone around the predicted path. This reaction has been proposed for two other, approved JLab experiments in Hall B and Hall C [64, 65]. The question we have to answer is what will be the likely precision of the NDE using this new reaction. The experiments cited above have very different kinematics. In the CLAS6 G_M^n measurement we saw a systematic uncertainty of about 1-1.5% which is a bit larger than the uncertainty we see in Fig. 2. Another calibration reaction to consider is $^2\mathrm{H}(e, e'p\pi^+\pi^-n)$. This method has been used to extract the NDE in a study of the $(e, e'p)$ and $(e, e'n)$ reactions on nuclei. It is an intriguing possibility, but the CLAS6 experiment achieved uncertainties in the NDE of 1-10% due primarily to low statistics. This uncertainty is too high for the G_M^n measurement. We have taken some initial steps studying these reaction last summer as part of an undergraduate summer research project.

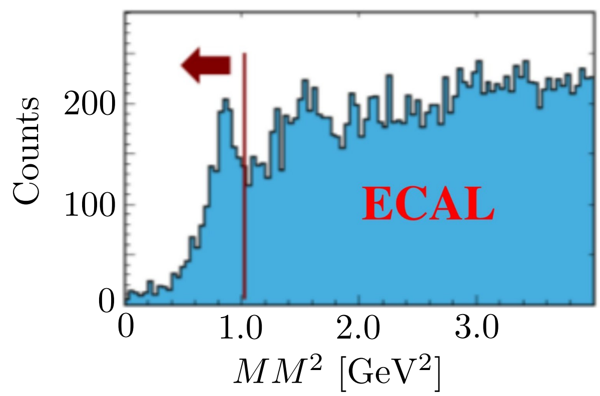

Figure 10: Tagged neutrons from the reaction $^2\mathrm{H}(e, e'\pi^+)nn$.

To summarize this portion of the renewal proposal, the motivation for the G_M^n measurement remains strong. We have begun the analysis of RGA and RGB data with collaborators from Florida International University (Raue and Baashen) to measure the NDE and extract G_M^n. We have already completed a preliminary measurement of the neutron detection efficiency using one of three RGA data sets. This work was the subject of a contributed talk at the fall, 2020 Division of Nuclear Physics meetings [2]. We have begun to study the event selection for the $e-n$ and $e-p$ events from the deuterium target. It is our goal to finish the analysis during the grant period proposed here.

2.2.2 CLAS12 Software Development

The Richmond group remains committed to the development of software to reconstruct, analyze, and simulate data from the CLAS12 detector. To that end we continue to work and plan with Dr. V. Ziegler who is the lead developer for the CLAS12 reconstruction code. Since 2017 our group's students have made five presentations at the fall, DNP meeting [5, 7, 8, 22, 26] and published two CLAS12-NOTEs on the SVT geometry [28] and unit test work [6] with another one in preparation on the study of the reconstruction resolution. See Section 2.1.2 for more details and Appendix B for a letter from Dr. Ziegler describing our collaboration.

We summarize the recent project on the reconstruction resolution here because it is relevant to the next project we propose. To measure the reconstruction resolution we started with the initial 3-momentum and track vertex vector from both the event generator and the reconstructed values after this event was simulated. We then 'swam' the two tracks through CLAS12 in simulation to a DC layer, took the difference between the intersection of each track and the layer, histogrammed the results, and used the widths of these distribution as the reconstruction resolution. We binned the outputs in a variety of different observables (θ, ϕ, ...) and studied the effect of different versions of the CLAS12 simulation, different particle species, different particle energy, *etc.*

The CLAS12 reconstruction code uses a Kalman filter to determine track parameters encoded in the state vector $t = \{x, y, tx = p_x/p_z, ty = p_y/p_z, p\}$ [27]. We propose to develop multi-dimensional functions for the components of the state vector to fill the covariance matrix needed at the starting point of the reconstruction code. The Kalman Filter is the optimal recursive estimator of the state vector of a discrete linear dynamic system [66] and relies on estimates of the initial state vector and initial covariance matrix to start the algorithm.

We now describe the Kalman filter. The track is described by parameters contained in the state vector t mentioned above. The code steps through the drift chamber track data and "connects the dots". In each step (*e.g.* a DC wire) the local hit data and the results from previous hit are used to predict where the next hit will occur and calculate the covariance matrix at that hit. A fourth-order Runge-Kutta calculation in the CLAS12 magnetic field is used [27]. The results are "filtered" - a weighted average is made of the predicted hit and the measured one and the covariance matrix is updated for the new hit. This process is followed to the end of the track [66, 67].

A drawback to the Kalman filter is the reliance on the initial value of the state vector and the covariance matrix [66]. We currently use the results of hit-based tracking and global estimates of the uncertainty to fill the initial covariance matrix. The goal here is to improve on that method and take advantage of recent upgrades to the CLAS12 simulation *gemc*. The impact of those changes was studied by the current Surrey masters student Adrian Saina (until mid-December 2020). See Fig. 4. We plan to build on Mr. Saina's work to develop an improved initial state vector and covariance matrix.

The procedure we plan to follow starts with simulating with *gemc* the components of the state vector in the tilted sector coordinate system (TSCS) in CLAS12. In these coordinates the z-axis is perpendicular to the detector planes (DC wire layers here) while the y-axis points along the mid-line of the sector, and x forms a right-handed coordinate system. As in the reconstruction resolution project we use the generated vertex and 3-momentum and the simulated-and-reconstructed results to swim two tracks to the first DC wire layer in Region 1 of CLAS12 (closest DC to the target). We rotate back to the lab coordinates and generate histograms of the components of the state vector as functions of x, y, θ, and ϕ. We use the width of the distributions and fit the results to get a smooth functional form. We will also study the impact of changes to the magnetic field polarity and other dependencies as the project develops.

The codes we develop will be tested and validated. In simulation we can make controlled "experiments" on the impact of changes to the elements of the initial covariance matrix and see how they effect the reconstruction results. For example, in Mr. Saina's work described above we measured in simulation the resolution for a variety of observables at many points in CLAS12. We can compare those results with the values we obtain when applying the upgraded Kalman filter.

2.2.3 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 harmonization 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). Experiment E12-06-117 has a rating of A^- from PAC36 [68]. 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. This experiment is part of Run Group E at JLab which recently underwent a jeopardy review (periodically done to all run groups in Hall B). The Program advisory Committee recommended to maintain the scientific rating and the awarded beam time [18].

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 proposed physics program is centered around the analysis of CLAS12 Run Group B data to extract the neutron electromagnetic form factor G_M^n. The data were collected during the current grant period. We will also maintain our contribution to developing software for simulation, reconstruction, and analysis of CLAS12 data. Our Richmond group consists of a single faculty member and 2-3 undergraduates working during the summers. The addition of a 10-month masters student would raise our productivity.

The University of Richmond is a primarily undergraduate institution and the Physics Department does not 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 US. The program director at Surrey, Prof. P. Stevenson, is enthusiastic about the opportunity for their masters students to work at JLab (see Appendix A). We request funds for an annual stipend and travel costs; there are no tuition costs.

We have thought carefully about how to structure this student's experience. (1) We station the person in the Richmond office at JLab. (2) Gilfoyle routinely travels to JLab (see Section 2.5); he spends about 40-50 days there in a normal year.(3) He is an active member of the CLAS12 Software group which provides a good working environment and community. (4) One of the JLab staff scientists, V.Ziegler, is committed to supporting this student. See Appendix B for a letter describing the collaboration. (5) The program proposed covers a wide range of topics. We work closely with the our collaborators to match the students' skills and interest to the program.

We received funding for two, ten-month, masters students in the current grant period for 2019 (Mr. Michael Armstrong) and 2020 (Mr. Adrian Saina). Mr. Armstrong's work is described in Section 2.1.2. It was published as a CLAS-NOTE [6] and presented at the fall, 2019 DNP meeting [7]. He is now a doctoral student at Bonn-Cologne Graduate School of Physics and Astronomy and is working at GSI. In 2020 Mr. Adrian Saina's did the work described in Section 2.1.2. His project was presented at the fall, 2020 DNP meeting [8] and is the topic of a CLAS12 note in preparation. He will complete his research year in December, 2020 and is planning to seek a PhD next year. It is worth noting that in 2016 one of the Surrey masters students, P. Davies, developed the geometry code for the Silicon Vertex Tracker (SVT) which is still in use [28, 69]. The program embeds the student in the JLab community with abundant opportunities for working with the PI and others.

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, Old Dominion, Princeton, and Stanford. Five have received doctorates and one (Keegan Sherman) is now pursuing his doctorate in nuclear physics at Old Dominion. Mr. Sherman recently received a research award from the DOE Office of Science Graduate Student Research Program.[70]. He is one of 52 awardees nationwide to receive the award. 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. Three have taken lucrative positions in industry (*e.g.* Omair Alam at Wolfram Research) 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 in normal years, attend collaboration meetings, present their work at group meetings and at local, national, and international conferences [3, 4, 5, 23, 24, 69, 71, 72, 73, 74, 75, 76, 77, 78], and are co-authors on technical reports [79, 80, 81, 82, 83]. 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 2022-2023 academic year. 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 32-node computing cluster obtained in 2010 with an NSF MRI grant. The University of Richmond is committed to maintaining the computational power of the cluster and we are actively building support to update the cluster. The system was used for nearly all projects described here and has been the one of the main development tools for CLARA, the service-based analysis framework for CLAS12 [84]. 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. 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 has a 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 normally spends about one day each week at JLab in addition to time spent on shift, at Collaboration meetings, *etc.* We take students on shift (when there is no pandemic) and attend Collaboration meetings at little cost.

2.6 Other Projects

We have several other projects the PI has been pursuing, but with the arrival of the RGB data and the G_M^n analysis there has limited time and resources to focus on that work including the analysis of CLAS6 data. The alignment of the SVT made considerable progress during the current grant period [85], but the PI again has to limit his future commitment to make progress on the G_M^n analysis. It is worth noting the PI will be on sabbatical in the 2022-2023 academic year which is during the proposed grant period.

2.7 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 analysis of the recently collected data on the neutron magnetic form factor G_M^n with CLAS12. As part of that work we are extracting the neutron detection efficiency from hydrogen data collected in CLAS12. We remain committed to the developing software for the simulation, reconstruction, and analysis of data from CLAS12. We request funds for a masters student to support this program and enhance our scientific productivity. As usual, undergraduates will be involved in all phases of the program we describe here.

3 Data Management Plan

The physics program described in this renewal application will generate large quantities of digital data with the start of CLAS12 production running. The largest volume of data generated by an experiment is the raw data containing the digitized readout from the data acquisition system and the reconstruction results. However, the raw data is only meaningful in the context defined by the meta data that is recorded as the data is taken, this includes accelerator parameters, operating conditions and calibration of the detector, operator logs and much more.

Jefferson Lab and the individual experimental halls have each developed data management plans appropriate for their own situation. The Scientific Computing group (SCI) in the JLab IT division has developed a JLab Data Management Plan that broadly outlines the steps taken to preserve data. Each hall has, in turn, generated a specific plan takes into account differences in the ways in which the halls operate their online and offline data processing. We will follow the data management plan appropriate for the source of our data. Below is a listing of the documents for JLab, Hall A, and Hall B with links to the files.

JLab data management plan:
`https://scicomp.jlab.org/DataManagementPlan.pdf`

Hall B data management plan:
`https://data.jlab.org/drupal/system/files/Data_Management_Plan_Hall-B_0.pdf`

Hall A data management plan:
`https://data.jlab.org/drupal/system/files/Data_Management_Plan_Hall-A.pdf`

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5 Publications Since Last Review

Refereed Journals

1. N. Zachariou et al. Beam–target helicity asymmetry E in $K^+ \Sigma^-$ photoproduction on the neutron. *Phys. Lett. B*, 808:135662, 2020.

2. S. Diehl et al. Extraction of beam-spin asymmetries from the hard exclusive π^+ channel off protons in a wide range of kinematics. *Phys. Rev. Lett.*, 125(18):182001, 2020.

3. M. A. Antonioli et al. The CLAS12 Silicon Vertex Tracker. *Nucl. Instrum. Meth.*, A962:163701, 2020.

4. V. D. Burkert et al. The CLAS12 Spectrometer at Jefferson Laboratory. *Nucl. Instrum. Meth.*, A959:163419, 2020.

5. V. Ziegler et al. The CLAS12 software framework and event reconstruction. *Nucl. Instrum. Meth.*, A959:163472, 2020.

6. A. Schmidt et al. Probing the core of the strong nuclear interaction. *Nature*, 578(7796):540–544, 2020.

7. M. Hattawy et al. Exploring the Structure of the Bound Proton with Deeply Virtual Compton Scattering. *Phys. Rev. Lett.*, 123(3):032502, 2019.

8. B. Schmookler et al. Modified structure of protons and neutrons in correlated pairs. *Nature*, 566(7744):354–358, 2019.

9. B. Zhao et al. Measurement of the beam spin asymmetry of $\overrightarrow{e}p \rightarrow e'p'\eta$ in the deep-inelastic regime with CLAS. *Phys. Lett.*, B789:426–431, 2019.

10. P. Roy et al. First Measurements of the Double-Polarization Observables F , P , and H in ω Photoproduction off Transversely Polarized Protons in the N* Resonance Region. *Phys. Rev. Lett.*, 122(16):162301, 2019.

11. M. Duer et al. Measurement of Nuclear Transparency Ratios for Protons and Neutrons. *Phys. Lett.*, B797:134792, 2019.

12. M. Duer et al. Direct Observation of Proton-Neutron Short-Range Correlation Dominance in Heavy Nuclei. *Phys. Rev. Lett.*, 122(17):172502, 2019.

13. N. Hirlinger Saylor et al. Measurement of Unpolarized and Polarized Cross Sections for Deeply Virtual Compton Scattering on the Proton at Jefferson Laboratory with CLAS. *Phys. Rev.*, C98(4):045203, 2018.

14. M. Duer et al. Probing high-momentum protons and neutrons in neutron-rich nuclei. *Nature*, 560(7720):617–621, 2018.

15. S. Lombardo et al. Photoproduction of K^+K^- meson pairs on the proton. *Phys. Rev.*, D98(5):052009, 2018.

16. E. Golovatch et al. First results on nucleon resonance photocouplings from the $\gamma p \rightarrow \pi^+\pi^-p$ reaction. *Phys. Lett.*, B788:371–379, 2019.

17. G. V. Fedotov et al. Measurements of the $\gamma_v p \to p' \pi^+ \pi^-$ cross section with the CLAS detector for 0.4 $\text{GeV}^2 < Q^2 < 1.0$ GeV^2 and 1.3 GeV $< W <$ 1.825 GeV. *Phys. Rev.*, C98(2):025203, 2018.

18. G.P. Gilfoyle. Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab. *EPJ Web Conf.*, 172:02004, 2018.

19. M. C. Kunkel et al. Exclusive photoproduction of π^0 up to large values of Mandelstam variables s, t and u with CLAS. *Phys. Rev.*, C98(1):015207, 2018.

20. S. Chandavar et al. Double K_S^0 Photoproduction off the Proton at CLAS. *Phys. Rev.*, C97(2):025203, 2018.

21. K. Park et al. Hard exclusive pion electroproduction at backward angles with CLAS. *Phys. Lett.*, B780:340–345, 2018.

22. P. Roy et al. Measurement of the beam asymmetry Σ and the target asymmetry T in the photoproduction of ω mesons off the proton using CLAS at Jefferson Laboratory. *Phys. Rev.*, C97(5):055202, 2018.

23. K. P. Adhikari et al. Measurement of the Q^2 Dependence of the Deuteron Spin Structure Function g_1 and its Moments at Low Q^2 with CLAS. *Phys. Rev. Lett.*, 120(6):062501, 2018.

24. S. Jawalkar et al. Semi-Inclusive π_0 target and beam-target asymmetries from 6 GeV electron scattering with CLAS. *Phys.Lett.B*, 782:662-667, 2018.

25. M. Hattawy et al. First Exclusive Measurement of Deeply Virtual Compton Scattering off ^{4}He: Toward the 3D Tomography of Nuclei. *Phys. Rev. Lett.*, 119(20):202004, 2017.

26. Robert Fersch et al. Determination of the proton spin structure functions for $0.05 \leq Q^2 \leq 5$ GeV^2 using CLAS. *Phys. Rev.*, C96(6):065208, 2017.

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

1. "CLAS12 Drift Chamber Reconstruction Software Unit Test", M.Armstrong†, G.P. Gilfoyle, and V.Ziegler, July 6, 2020.

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

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

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

3. M.Heyrich*, X.Hu*, and G.P.Gilfoyle, "Event Selection in Electron Scattering on Deuterium", Bull. Am. Phys. Soc., Fall DNP Meeting, HA.00107 (2019).

4. M.Armstrong†, V.Ziegler, and G.P.Gilfoyle, "CLAS12 Drift Chamber Reconstruction Code Validation", Bull. Am. Phys. Soc., Fall DNP Meeting, HA.00075 (2019).

5. B. Weinstein*, A. Balsamo*, and G.P.Gilfoyle, "Software to Monitor CLAS12 Data Quality", Bull. Am. Phys. Soc., Fall DNP Meeting, HA.00136 (2018).

6. A.Balsamo*, K.Sherman*, and G.P.Gilfoyle, "Analysis of Quasi-Elastic e-n and e-p Scattering from Deuterium", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00032 (2017).

Invited Presentations

1. G.P. Gilfoyle. "Hunting for Quarks and Gluons", Physics Seminar, University of Surrey, Guildford, UK, May 8, 2018.
2. G.P. Gilfoyle. "Hunting for Quarks and Gluons", Physics Seminar, University of Richmond, Richmond, VA, USA, September 2, 2020.

Service Work

1. Run Group B Run Coordinator, Jan 2-13, 2020.
2. Run Group B Run Coordinator, Mar 3-11, 2019.
3. Reviewer, Phys Rev Lett.

6 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	Volker Burkert	Raffaella De Vita
Evgeny Golovach	Daniel Carman	Latifa Elouadrhiri
Veronique Ziegler	J.W. Van Orden	Nathan Harrison
John Arrington	Mark Ito	Gagik Gavalian
Marco Battaglieri	Kawtar Hafidi	Maurizio Ungaro
David Heddle	Graham Heyes	S.E.Kuhn
Brian Raue	Lamya Baashen	Andrey Kim

A listing of the members of the CLAS Collaboration is 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	T. Hayward	V. Batourine	M. Contalbrigo
D. Riser	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
M. Williams	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
A. Movsisyan	O.P. Dzyubak	H. Egiyan	P. Eugenio
R. Fatemi	G. Fedotov	R.J. Feuerbach	Z. Akbar
M. Garcon	G. Gavalian	K.L. Giovanetti	F.X. Girod
J.T. Goetz	Y. Gotra	A. Gonenc	R.W. Gothe
K.A. Griffioen	M. Guidal	M. Guillo	N. Guler
L. Guo	V. Gyurjyan	C. Hadjidakis	N.Markov

R.S. Hakobyan	J. Hardie	J. Newton	P. Mattione
K. Hicks	I. Hleiqawi	M. Holtrop	A. Afanasev
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. Khachatryan	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
H. Avagyan	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
S. Schadmand	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	T. Mineeva	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
A. Radic	M.H. Wood	A. Yegneswaran	J. Yun
L. Zana	J. Zhang	B. Zhao	Z. Zhao

7 Biographical Sketch: Dr. Gerard P. Gilfoyle

Position	Professor, University of Richmond.
Degrees	Ph.D., Exp. Nuclear Physics, Univ. of Pennsylvania, 1979-1985, H.T.Fortune, advisor. A.B., cum laude, Franklin and Marshall College, 1979.
Experience	2018-present - Robert and Lena Loving Chair of Physics. 2015-2016 - Scientific Consultant, Jefferson Laboratory (JLab). 2008-2015 - 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. 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). 2015-2016 - JSA/SURA Sabbatical Support ($13,500). 2014-present - JSA/SURA Initiatives Fund award ($10,000). 2009-2011 - National Science Foundation MRI grant ($162,000). 2009-2010 - Jefferson Laboratory Sabbatical Support. 2009-2010 - JSA/SURA Sabbatical Support ($13,500 and $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	2015-2017 - Chair, CLAS Collaboration Reviewer, Physical Review Letters 2013 - Chair CLAS Collaboration nominating committee 2005-present Reviewer, US Department of Energy and NSF. 2006-2010 - Chair, Nuclear Physics Working Group of the CLAS Collaboration 2005-present - Reviewer, JSA/SURA Grad Fellowships and Initiatives Funds. 2000-2006 - Chair, Department of Physics. 2002-2003 - American Physical Society Task Force on Countering Terrorism. 2000 - Reviewer, US Department of Defense.
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. V. Ziegler et al. The CLAS12 software framework and event reconstruction. *Nucl. Instrum. Meth.*, A959:163472, 2020.
2. A. Schmidt et al. Probing the core of the strong nuclear interaction. *Nature*, 578(7796):540–544, 2020.
3. D. Adikaram et al. Towards a resolution of the proton form factor problem: new electron and positron scattering data. *Phys.Rev.Lett.*, 114(6):062003, 2015.
4. O.Hen et al. (CLAS Collaboration), "Momentum sharing in imbalanced Fermi systems", Science **346**, 614 (2014).
5. 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).
6. G.P. Gilfoyle, "Few-body physics with CLAS", Few Body Syst. 50 (2011) 15-22.
7. 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).
8. 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).
9. B. Mecking, *et al.*, (The CLAS Collaboration), 'The CEBAF Large Acceptance Spectrometer', Nucl. Instr. and Meth., **503**/3, 513 (2003).
10. G.P.Gilfoyle and J.A.Parmentola, 'Using Nuclear Materials to Prevent Nuclear Proliferation', Science and Global Security **9**, 81 (2001).

Selected Invited Presentations

1. "Hunting for Quarks: New Physics at Jefferson Lab", Physics Dept., University of Surrey, Guildford, UK, May 8, 2018.
2. "Hall B Organization", CLAS12 Ready-for-Science Review, Jefferson Lab, September 25, 2017.
3. "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors (G_M^n) at Jefferson Lab", European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Trento, Italy, Apr 21, 2016.
4. "CLAS12 Track-Based Alignment", CLAS12 Workshop, Jefferson Lab, Newport News, VA, Oct 20, 2015.
5. "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.

8 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
P. Davies	Feb, 2016	Feb, 2016	Masters	June, 2016	Gilfoyle/Regan
C. Platt	Feb, 2017	Feb, 2017	Masters	June, 2017	Gilfoyle/Regan
M. Armstrong	Feb, 2019	Feb, 2019	Masters	June, 2019	Gilfoyle/Stevenson
A. Saina	Feb, 2020	Feb, 2020	Masters	Expected June, 2020	Gilfoyle/Stevenson

9 Current and Pending Support

We have no pending proposals at this time.

Our current support is this grant.

Sponsor	US Department of Energy
Award Number	DE-FG02-96ER40980
Award Title	Medium Energy Nuclear Physics Research at the University of Richmond
Award Amount	$275,000
Effort	57 person months over three years

By the end of this funding period (5/31/2021) we expect to have the following funds remaining in equipment, travel and undergraduate stipends shown in Table 4. An explanation is below.

	Grant	Item	Amount
1.	Current Grant	Supplies	$4,443
2.	Current Grant	Travel	$22,000
3.	Current Grant	Student Stipends	$1,000

Table 4: 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. With the start of data taking for Run Group B (shift expert and run coordinator duties) and the COVID-19 pandemic we did not spend nearly as much for conference travel.

Item 3. The University supports student summer research with stipends awarded on a competitive basis. My research students received limited support over the last three years for such funding from the University.

10 Facilities and Resources

10.1 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 2.5 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 is committed to maintaining the computational capabilities of the cluster.

The University supports undergraduate summer stipends and student travel. 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 has a policy of returning 10% of indirect costs from external grants back to the PI.

10.2 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.

11 Equipment

The nuclear physics group at the University of Richmond is supported by a computing cluster obtained in 2010 with an NSF MRI grant. The system consists of 32, dual-6-core, remote nodes each with 24 GByte of RAM and 1 TByte of storage, a head node, and a file server with 5 TByte of space. The University of Richmond is committed to maintaining the computational power of the cluster. The system was used for nearly all projects described here and has been the one of the main development tools for CLARA, the service-based analysis framework for CLAS12 [84]. 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.

Appendices

A Confirmation Letter from the University of Surrey

UNIVERSITY OF SURREY

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Dr. Gerard P Gilfoyle
138 UR Drive
University of Richmond
Richmond, VA 23173
USA

Thursday 15 October 2020

Dear Prof Gilfoyle

On behalf of the Physics Department at the University of Surrey, UK, I write to commend and support your ongoing programme of research funded through the Department of Energy, which is currently up for renewal. In particular, I would like to confirm our desire to continue to collaborate with you by placing University of Surrey Master of Physics (MPhys) research students with you at the University of Richmond, and working at JLab. I think you will agree that the placement programme has been of great mutual benefit for us both. Certainly from our point of view, the ability to send our bright students on the Master of Physics programme to work with you has been of great benefit to the students, who have enjoyed your direct supervision as a member of a world-class research project at a leading laboratory. It also enhances the prestige of our MPhys programme.

As I'm sure you know, the MPhys programme at Surrey is available only to the highest-achieving of our cohort of physics students. Under the UK system, such students may choose to work directly towards a master's degree without formally exiting with a bachelor's degree first. When our students go on their research placement, they have satisfied the requirements for an ordinary BSc degree, and are then continuing their studies to work for a master's degree. Our programme of sending all our qualified master's students on placement is a unique part of the offering at Surrey, as laid down in the charter upon the founding of the University which enshrined that we should give the opportunity of employment in the form of external placements to all students that they better understand the world of work outside the confines of the lecture theatre. Being able to offer placements in research environments allows our students to experience their hoped-for career path in scientific research, before completing their last semester of study in Surrey and graduating. It is often the case that the students then return to the site of their research placement to enrol as PhD students.

Our link with your group extends back to 2013, and we would be delighted if it could be renewed for our future cohorts of students. Since we began working with you, the numbers of students enrolling in Physics at Surrey in general, and those qualified to be on the master's programme in particular have increased significantly. We have enjoyed building links with many excellent research labs at Universities, government and private facilities around the world, and you may be interested to know some of the recent company you have amongst placement providers: In the US, Michigan State University, UMass Lowell, Notre Dame, Oak Ridge National Lab, Central Michigan University, University of Texas, Dallas, and Applied Materials, Boston, have hosted our students in the last two years; elsewhere in the world, Triumf (Canada), the Institute of Astrophysics (Canary Islands), Australian National University, Peking University (China), INFN Legnaro (Italy), the University of Marburg (Germany), the University of Bologna (Italy), are amongst those who have hosted, and there are many more private and public companies and institutes in the UK.

The formal mechanisms of the programme remain as they have for the previous students you have hosted: The students remain enrolled at the University of Surrey and make use of the work they perform under your guidance to gain the credits necessary to contribute 120 of the credits needed for their master's degree. The placements run over two semesters, and the summer period, encompassing nearly a full calendar year: From early February to late December.

I, on behalf of the Department of Physics at the University of Surrey, wish you the best with your DoE proposal and hope that we are able to continue our mutually-beneficial programme of student employment in your group.

Yours sincerely,

Dr Paul Stevenson
University of Surrey

B Collaboration Letter from Jefferson Lab

Jefferson Science Associates

Thomas Jefferson National Accelerator Facility

November 17, 2020

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 has been successful since 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) which is focused exclusively on the scientific program at Jefferson Lab. I am a scientific staff member at Jefferson Lab (JLab) in Hall B. I am part of the CLAS12 software group, leading event reconstruction efforts and contributing to the use of novel techniques such as AI in track reconstruction in the forward detector. I was already leading the CLAS12 track reconstruction effort when this Richmond/Surrey program at JLab was started.
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 ten months working in a laboratory and writing a thesis based on their work. Students participating in this program are at a level roughly equivalent to an advanced undergraduate or a new graduate student in the US. After their research year they defend their thesis before a committee during their final semester at Surrey.
Since 2013 three Surrey masters students have been supported by Dr. Gilfoyle's DOE grant. In each case Dr. Gilfoyle was the official mentor, but all three were part of the software group and engaged with physicists, engineers, and technicians in the CLAS Collaboration and throughout Jefferson Lab. In each case Dr. Gilfoyle and I coordinated the Surrey students' projects with the priorities of the Software Group and in particular on preparations for the arrival of beam in CLAS12. Mr. Alex Colvill's M.Phys thesis (2013) was on the development of the stand-alone reconstruction software for the time-of-flight (TOF) subsystems in CLAS12. He adapted the existing Fortran-based algorithms from the previous detector in Hall B to our new service-based architecture using the Java language. He received first honors for his thesis and it was

adapted to a CLAS Collaboration technical report (CLAS12-NOTE 2014-013). Mr. Peter Davies' work (2016) was on the geometry model and software tools for the Silicon Vertex Tracker (SVT) in CLAS12. His project started with an early set of the core parameters and the relationships among them for the SVT and he developed the tools to produce the inputs needed for the CLAS12, physics-based simulation and the methods needed for the SVT reconstruction code. He was able to resolve differences between the early set of geometry parameters and the current design of the SVT by working with the JLab designers. He has completed the Surrey masters program and his M.Phys thesis has also been published as a CLAS-NOTE (CLAS12-NOTE 2017-008). Mr. Charles Platt's project (2017) is testing and validating the SVT geometry code and integrating it into the SVT reconstruction algorithms. Mr. Michael Armstrong (2018) developed unit tests for tracking. These are essential to ensure code coverage. Mr. Adrian Saina (2020) is doing extensive studies of tracking resolution. His results are used to validate tracking performance.

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. 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 data taking in CLAS12.

Sincerely,

Dr. Veronique Ziegler
Staff Scientist
Jefferson Science Associates

C Summary of Publications

Name	Letter Publications	Other Refereed Journals	Invited Talks	CLAS12 NOTES
Faculty				
G.Gilfoyle	15(0)	11(4)	2	1(1)
Masters Students				
M.Armstrong				1(1)
A.Saina*				
Total	15(0)	11(4)	2	1(2)

Table 5: Summary of publications during the current grant period. In parenthesis is the number of publications in which the listed author played a substantial role.

*Mr. Saina will complete his work in December, 2020.

D Budget Justification

YEAR 1 (June 1, 2021 - May 31, 2022)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $19,200 whichever is smallest. Fringe benefit rate for senior personnel is 7.9%.

B.2 One masters student for four months (Feb-May, 2022) at an annual stipend of $31,300 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, 2021 - May 31, 2022 so the programs are out of phase. We expect a masters student to arrive by February, 2022 so four months of their research year would be covered in the first year of this contract and the remainder in the second year of the contract. There are no tuition costs for this student. This student is classified as professional personnel because they are not Richmond students. Fringe benefit rate is 27.4% for the Surrey masters student.

B.3 Two undergraduate students for 10 summer weeks. Fringe benefit rate is zero for the undergraduates.

D.1 Domestic travel:

1. $1000 - Round trip mileage charge from Newport News, VA to Richmond for the masters student to work with the PI and his undergraduate researchers and attend seminars at Richmond. Prorated for the time in the program during the 2021-2022 grant year.
2. $1100 - Travel expenses for the masters student to attend one conference to present their findings. Prorated for the time in the program during the 2021-2022 grant year.
3. $2000 - Domestic travel expenses for routine travel to JLab. We assume limited travel at the start of the first year of the grant due to COVID-19, but expect in-person meetings to return in 2022. CLAS12 will run in fall, 2021 (scheduled for June - October of 2021) and the CLAS Collaboration will likely request volunteers for shifts from 'nearby' institutions. In a similar situation this year (2020) Gilfoyle volunteered for seven shifts. The money requested here will cover costs for twelve shifts in three sets of four.

   Total = $4,100

D.2 Foreign travel:

1. $2,200 - Travel expenses for one foreign invited talk. We assume limited travel at the start of the first year of the grant due to COVID-19, but expect in-person conferences to return in 2022. Over the last six years Gilfoyle has given nine invited talks at conferences, universities, and JLab reviews including three outside the US. 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.

F.1 - $1,854 - 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).

H - Indirect costs: 52% of wages, salaries, and fringe benefits for the PI, undergraduates, and Surrey masters student (who will spend more than 50% of their time away from the University of Richmond campus).

YEAR 2 (June 1, 2022 - May 31, 2023)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $19,200 whichever is smallest. Fringe benefit rate for senior personnel is 7.9%.

B.2 One masters student for six months (June-December, 2022) followed by a second student (February-May, 2023) both at an annual stipend of $31,300 prorated for their time in the program during the 2022-2023 grant year. In the Surrey program the students' research year runs February to December. The dates for this contract are June 1, 2022 - May 31, 2023 so the programs are out of phase. We include the support for the full research year in the 2022-2023 grant period and it is split between the end of the first student's time at JLab (2022) and the beginning of the second (2023). There are no tuition costs for this student. This student is classified as professional personnel because they are not Richmond students. Fringe benefit rate is 27.4% for the Surrey masters student.

B.3 Two undergraduate students for 10 summer weeks. Fringe benefit rate is zero for the undergraduates.

D.1 Domestic travel:

1. $2000 - Round trip mileage charge for the masters student to travel to Richmond to work with the PI and his undergraduate researchers and attend seminars at Richmond.
2. $2200 - Travel expenses for the masters student to attend one conference to present their findings.
3. $8000 - Travel expenses for sabbatical and the summer at JLab during the 2022-2023 academic year. Gilfoyle will be on sabbatical at JLab during 2022-2023. 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 $13,000. There are some existing University funds ($5,000) that can be used for this purpose leaving $8,000 in travel cost remaining. To calculate the cost for travel to JLab we made the following assumptions for the sabbatical part: (1) 30 weeks spent at JLab in 2022-2023, (2) hotel rate of $69 per night (JLab negotiated rate), (3) mileage reimbursement rate of $0.54/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.

   For the summer 2022 costs we assumed (1) 11 weeks, (2) one-round trip per week, (3) 150 miles per round trip, (4) mileage reimbursement rate of $0.54/mile (University of Richmond rate), (5) summer hotel rate of $79 per night (JLab negotiated rate), (6) Seven total nights in hotels (one Collaboration meeting and one set of shifts).

   Total = $12,200

D.2 Foreign travel:

1. $2,200 - Additional travel expenses for one foreign invited talk. Over the last six years Gilfoyle has given nine invited talks at conferences, universities, and JLab reviews including three outside the US. 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.

F.1 - \$2,387 - 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).

H - Indirect costs: 52% of wages, salaries, and fringe benefits for the PI, undergraduates, and the Surrey masters student (who will spend more than 50% of their time away from the University of Richmond campus).

YEAR 3 (June 1, 2023 - May 31, 2024)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or \$19,200 whichever is smallest. Fringe benefit rate for senior personnel is 7.9%.

B.2 One masters student completing their research year (six months in 2023). The stipend for the student is prorated for the time in the program during the 2023-2024 grant year. In the Surrey program the students' research year runs February to December. The dates for this contract are June 1, 2023 - May 31, 2024 so the programs are out of phase. There are no tuition costs for this student. This student is classified as professional personnel because they are not Richmond students. Fringe benefit rate is 27.4% for the Surrey masters student.

B.3 Two undergraduate students for 10 summer weeks. Fringe benefit rate is zero for the undergraduates.

D.1 Domestic travel:

1. \$1000 - Round trip mileage charge for the masters student to travel to Richmond to work with the PI and his undergraduate researchers and attend seminars at Richmond. Prorated for the time in the program during the 2021-2022 grant year.
2. \$1100 - Travel expenses for the masters student to attend one conference to present their findings. Prorated for the time in the program during the 2021-2022 grant year.
3. \$4000 - Domestic travel expenses for routine travel to JLab and invited talks for the PI. Over the last six years Gilfoyle has nine invited talks at conferences, universities, and JLab reviews. He routinely spends spends one day per week at JLab, attends three CLAS Collaboration meetings each year, takes 8-12 expert shifts, and acts as run coordinator. 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 = \$6,100

D.2 Foreign travel:

1. \$2,200 - Additional travel expenses for one foreign invited talk. Over the last six years Gilfoyle has given nine invited talks at conferences, universities, and JLab reviews including three outside the US. 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.

F.1 - \$2,731 - 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).

H - Indirect costs: 52% of wages, salaries, and fringe benefits for the PI, undergraduates and the Surrey masters student (who will spend more than 50% of their time away from the University of Richmond campus).