Medium Energy Nuclear Physics Research at the University of Richmond

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Contents

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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 and extract components of the deuteron wave function. In experiment E12-07-104 (spokesperson: Gilfoyle) we will measure the neutron magnetic form factor at high Q^2. We are now part of the group developing software to reconstruct, simulate, and analyze the data from the new CLAS12 detector at JLab. We have also involved in the calibration and commissioning of CLAS12 and preparations for the engineering run and first experiment.

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 primarily the new 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 student. Two Surrey students (Peter Davies and Charles Platt) 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
Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)	CLAS-Approved Analysis[1]
CLAS12 Software	
Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)	E12-06-117
Precision measurement of the neutron magnetic form factor up to $Q^2 = 18\ (GeV/c)^2$ 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 (2014). Our major focus now is on preparations for the CLAS12 engineering run, first experiment, and the measurement of G_M^n, the magnetic form factor of the neutron. We are part of a broad program at JLab to

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

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 G_M^n experiment in Hall B using the CLAS12 detector (JLab Experiment E12-07-104) and is a co-spokesperson on the Hall A measurement (E12-09-019) of G_M^n. 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.

To prepare for the G_M^n experiment we have developed an end-to-end software chain from target simulation to post-reconstruction analysis using the Collaboration's CLAS12 Common Tools software [2]. We have also begun the task of simulating the calibration reactions we propose to use for the G_M^n experiment [3, 4, 5, 6, 7, 8].

Since our last renewal we have written the code and compiled the parameters that describe the geometry of the Silicon Vertex Tracker (SVT). CLAS12 consists of a variety of subsystems in the base system with more than 100,000 readout channels. A Forward Detector is used for scattering angles $5^\circ - 40^\circ$ and a Central Detector for large angles ($35^\circ - 125^\circ$). The SVT measures points on the trajectory of charged particles moving in the Central Detector's solenoid field to determine the momentum and vertex of a track. We have developed the geometry model of the SVT (based on guidance from the JLab designers), entered the parameters into the CLAS12 database (ccdb), and written codes to make the geometry accessible to the CLAS12 physics-based simulation (called *gemc*) and the CLAS12 reconstruction code. We have also developed codes to align the SVT to reach its design specifications.

A possible schedule for CLAS12 production running holds the possibility of using a deuterium target in the next 2-3 years. This run may not use the ideal run conditions for the G_M^n measurement, but we have joined the group to enhance our preparations. In the summer of 2016, the PI had primary responsibility for preparing the beamtime request required before an experiment at JLab can be considered for scheduling. The request was successful.

In the summer of 2015, the PI was elected chair of the CLAS Collaboration. The Chair is the collaboration spokesperson and the principal contact to the Jefferson Lab directorate for the CLAS Collaboration. He/she has overall responsibility for assuring smooth operation of the Collaboration. The PI was responsible for organizing a host of reviews and discussions to make the transition to the CLAS12 era of operations.

One of the projects that is far along (see Table 1) is entitled "Out-of-Plane Measurements of the Structure Functions of the Deuteron" based on the data taken with CLAS6, the previous detector in Hall B. However, with the rapid approach of the start of production running in CLAS12 and the responsibilities of CLAS Chair, progress has been limited. The PI's tenure as CLAS Chair ended in September 2017 and we will refocus some of our time on this work.

We now summarize our Plan of Work. We will continue our preparations for the G_M^n experiment including more complete simulations of the analysis, studies of calibration reactions, and characterization of the background. We will also continue the work on the SVT alignment to reach its design performance. We will also push forward on the CLAS6 analysis project.

We also ask for 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 are required to spend ten months engaged in research. These students' work is matched to their interests, the program proposed here, and the activities in our collaboration at JLab. The addition of these students (one per year) would raise our scientific productivity. The Surrey program has been successful in the nuclear structure community at Yale, Kentucky, Florida State, Notre Dame, LBL, and even Richmond (through a faculty colleague, Dr. Con Beausang). Those programs benefited from the Surrey students and many of the students have gone on to US graduate schools, enhancing the US workforce.

2 Project Description

2.1 Status of Current Projects

The research effort in medium energy nuclear physics at the University of Richmond is part of the program at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA. We now discuss our work to prepare for the new CLAS12 detector. 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 preparation for the start of the 12 GeV era has grown. In an internal review of computing in May, 2011, the committee stated that "it is the desire of the laboratory to have all computing systems and software ready, so that the time from beam on target to physics journal articles is as short as possible" [10, 11, 12, 13, 14, 15]. We are committed to that goal.

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 [16], it is Milestone HP4 in the DOE Performance Measures [17], and it forms a central part of the future physics programs at Jefferson Lab (JLab) [18, 19, 20]. 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 [19, 20]. 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 [21]. The experiment has an A^- rating from the Program Advisory Committee (PAC) and was awarded 30 days of beamtime to be scheduled in the first five years running of CLAS12 [22]. A large portion of our work revolves around preparations for CLAS12 operations in general and the G_M^n measurement in particular. We are also members of the collaboration to measure G_M^n in Hall A (E12-09-019).

To extract G_M^n we form the ratio of $e-n$ to $e-p$ quasielastic scattering (QE) from deuterium. Neutrons are detected separately in the CLAS12 calorimeters and Forward Time-of-Flight (FTOF) systems [21]. We have developed an end-to-end simulation of the experiment. QE events are generated with realistic Fermi motion and the CLAS12 response simulated with the CLAS Collaboration's physics-based simulation *gemc* [7, 8, 23, 24]. The output is reconstructed with the CLAS12 Common Tools and analysis of the 4-vectors done with groovy scripts built on the Common Tools[2, 25, 26]. This software has been the focus of an undergraduate project for the last two years and the initial development is complete [7, 8]. We are now testing and validating.

One of the important challenges in the G_M^n experiment is to measure the neutron detection efficiency (NDE). We proposed the $^1\mathrm{H}(e, e'\pi^+ n)$ reaction as a source of tagged neutrons [27] to measure NDE in the CLAS12 calorimeters and the FTOF. We are developing a full chain simulation from event generation (using PYTHIA 6.4) to final NDE and find a preliminary average NDE around 50% for the CLAS12 calorimeters [28]. We continue to validate and test this analysis [4, 6].

To measure the NDE requires a proton target and we have proposed a unique, dual $LH_2 - LD_2$ target so that calibration data can be measured simultaneously with the production data ensuring both data sets are collected under the same run conditions [4, 5, 6]. One of the goals for the current grant period was to begin design of the G_M^n target. We have a preliminary target design done by the JLab technical staff and have developed a full simulation of that design using *gemc* and the other Common Tools [5]. Figure 1 shows the target[3, 5]. We have performed initial tests of the impact of background events generated by the target components and found their effect to be limited. This software package is now included in the standard CLAS12 Common Tools software distributions.

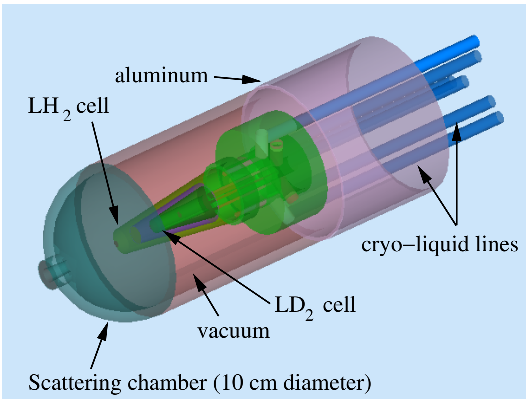

Figure 1: Dual-cell target for Hall B G_M^n experiment in the *gemc* simulation.

We have also been part of the group developing the reconstruction code for the CLAS12 Time-of-Flight (TOF) subsystem which builds on our earlier experience with this system [29]. The Forward TOF system is relevant for the G_M^n measurement because it will be used to detect neutrons for the ratio measurement (albeit at a lower efficiency than the calorimeters). The standalone TOF analysis was the thesis topic of a Surrey masters student and a technical report [29, 30, 31]. The primary developer during this grant period was E. Golovach of Moscow State University. The PI (Gilfoyle) organized bi-weekly meetings of the TOF group (technical lead: D. Carman) during the 2015-2016 academic year. The group updated the analysis code to the CLAS12 Common Tools, performed matching between the panels of TOF counters in the CLAS12 Forward Detector, and established baseline performance of the TOF subsystem via simulation with *gemc*.

2.1.2 Geometry and Alignment of the Silicon Vertex Tracker

In developing the Plan of Work for the current grant period we met with the CLAS12 Software Group leader (JLab staff scientist V. Ziegler) and others to plan how to meet the Laboratory readiness goal. We decided to focus on track-based alignment of the Silicon Vertex Tracker (SVT) in the Central Detector. Reaching the CLAS12 design specifications requires understanding the geometry of the detector components as they are built and installed and during their operation. Differences between the nominal geometry and the detector built in Hall B can degrade the resolution and lead to biases in the reconstruction of the data. These differences could effect the physics results.

The SVT is a silicon strip detector composed of three, concentric regions of 10, 14, and 18 sectors. Each sector in a region has two silicon layers with 256 strips in each layer (over 21,000 readouts). The sectors form a barrel parallel to the beamline and centered on the target position. Silicon technology is needed to satisfy the demands for high luminosity, angular precision/segmentation, and low material budget to reduce multiple scattering. Precise understanding of the SVT geometry is required to meet the design specifications. We have developed a software model of the SVT that provides the geometry to both the CLAS12 simulation code (*gemc*) and the Common Tools reconstruction code from the same core parameters stored in the CLAS12 Constants Database (ccdb). Our code is written in Java (like the reconstruction code) and includes methods to read the core geometry parameters from ccdb, calculate the endpoints of the silicon strips, analyze survey data, and generate the data, scripts, and input files needed by *gemc*. The work was largely done by the PI and the Surrey masters student Peter Davies [32, 33]. This code is now a standard part of the CLAS12 Common Tools and routinely used by the Collaboration.

To validate the code we used visual inspection with Root, interactive graphics in *gemc*, geantinos in *gemc*, and simulation studies. We also coordinated our geometric model with the JLab designers. Each layer in the SVT has three fiducial marks on it. Panel (a) in Figure 2 shows the components of the vector difference between the expected positions of the fiducials from the JLab designers and the same points calculated from the original, CLAS12 geometric model. The horizontal axis is the

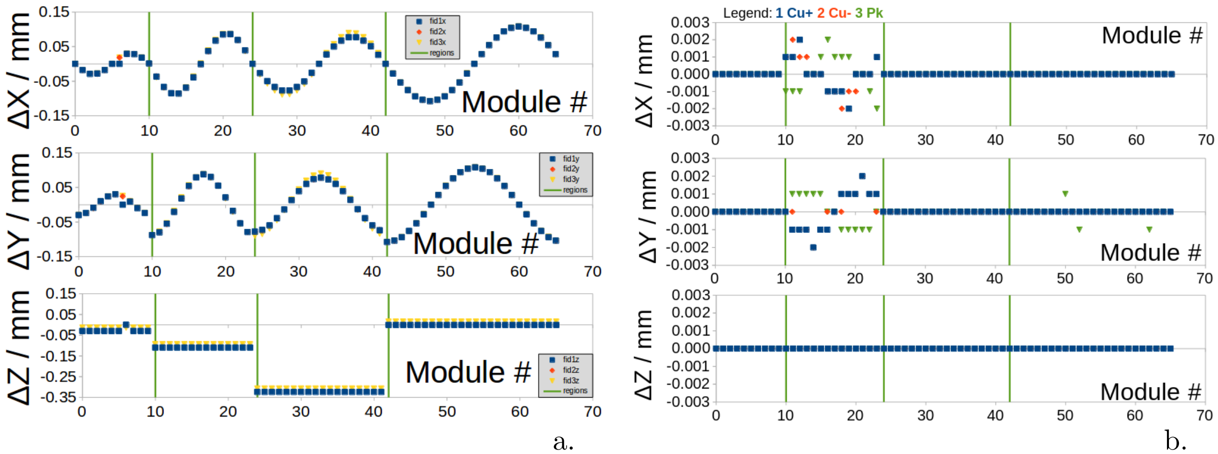

Figure 2: Comparison of fiducial data is shown in Panel (a) between original CLAS12 model and designer data and (b) after resolution of differences.

sensor index (1-66) in the original, four-region configuration of the SVT. The fourth region will not be used in CLAS12. There are large differences with some exceeding 300 μm - well outside design specifications. Working with the JLab designers we resolved the differences and eventually found the result shown in Panel (b) of Figure 2. Nowhere do the differences exceed 3 μm and most are zero. These results are well within the specifications for the SVT. These parameters are now stored in the CLAS12 database ccdb and used by the entire Collaboration.

Finding the corrections to the SVT mis-alignments is the goal of the alignment project. We chose the closed form approach to alignment where a least squares fit is performed simultaneously on the track parameters and on the detector geometry parameters together. This approach can account for correlations among the parameters, but for a detector like CLAS12 the number of detector parameters is large so the computational demands may be prohibitive. The path we have taken is to use Millepede II (`millepede`), a program for linear least squares fits with a large number of parameters based on the minimization of the χ^2 [34, 35, 36].

We developed the software analysis chain to extract the misalignments using `millepede` and correct for them in the Common Tools reconstruction code for a subset of cosmic ray events. This analysis chain consists of the following steps. We start with (1) a cosmic-ray simulation in the SVT using *gemc* or real data from the SVT, (2) reconstruct those events with the Common Tools, and then (3) select an event type. Here we use type-1 events which are cosmic rays with hit clusters in eight, horizontal SVT modules as shown in Figure 3a. These events are easier to interpret and debug. Next, (4) the data for those events are combined with additional information required for `millepede`. This information consists of the derivatives of the formula for the distance-of-closest-approach (DOCA) between a silicon strip in the SVT and the straight-line track of the cosmic ray. The derivatives are with respect to the parameters of the fit and the geometry. The geometry parameters here are the three-dimensional endpoints of the silicon strip. The results are (5) written in binary format as input to `millepede` which (6) reads in this file and determines the best-fit parameters for the geometry. These are expressed as shifts in the geometry parameters which are then (7) added to the geometry in the reconstruction.

We have tested the code for type-1 events with simulated and real cosmic rays. We simulated cosmic rays with the ideal geometry (no misalignments) and as expected we see residuals centered

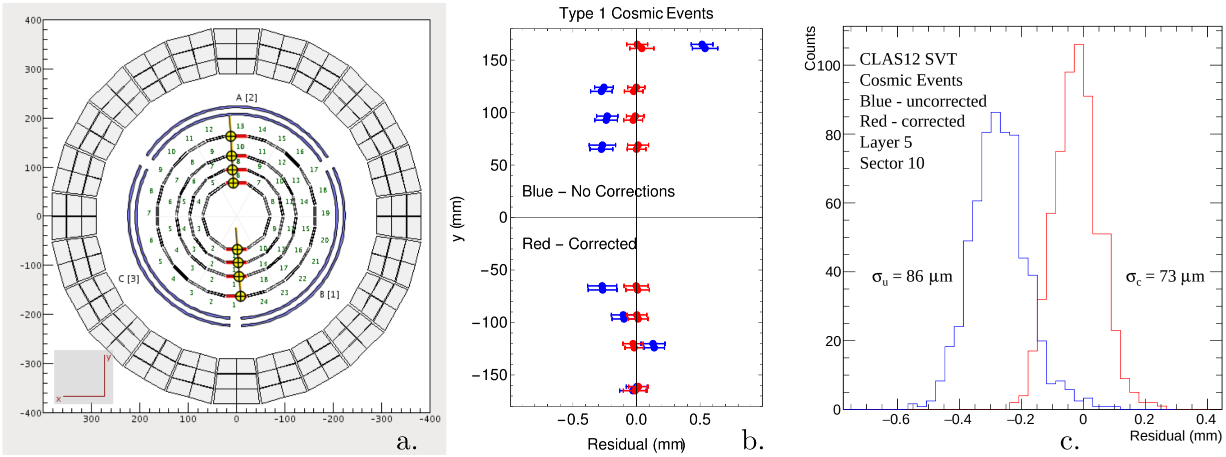

Figure 3: Panel (a) shows a Type 1, cosmic ray in the SVT passing though all eight horizontal SVT modules in the original four-region configuration. Panel (b) shows the residuals for measured SVT cosmic rays. Blue points show the initial residuals. Red points show the same residuals after correcting with the `millepede` results. Panel (c) shows cosmic-ray residuals in a single layer in SVT before (blue) and after (red) correcting for misalignments.

at zero with the expected widths. We inserted a known shift in the *gemc* geometry and saw the expected shifts in the reconstructed residuals. A more complete test was done with real cosmic-ray data. The blue points in Figure 3b shows the residuals with the original, ideal geometry along the horizontal axis. The vertical axis is the vertical position of the modules in the SVT. Compare with panel (a) in the figure. The uncertainties on each point are not the uncertainties on the residuals, but rather the width of a Gaussian fit to the distribution for that sector and layer. This value is more central to the goal of aligning the SVT. Some of the modules have residuals shifted by nearly 300 μm from zero. These misalignments were corrected by taking the results of the `millepede` fits and applying shifts to the SVT geometry used in the reconstruction. The results are shown as the red points in Figure 3b. These points are now aligned with zero. A closer look at one of the layers is shown in Figure 3c. It shows the residual distribution for Layer 5 in Sector 10 (see Figure 3a) before the correction for the misalignments in blue and after the correction in red. The distribution is shifted from a centroid of ≈ -300 μm to close to zero. The shifted distribution is more narrow and approaches the design goal of about 65 μm. In summary, we have developed the complete alignment chain for this subset of events and demonstrated that we can correct for the SVT mis-alignments in the CLAS12 reconstruction.

2.1.3 CLAS Collaboration Chair

In June, 2015 the PI (Gilfoyle) was elected the chair of the CLAS Collaboration. The chair is the main contact point between the CLAS Collaboration and the JLab management and he/she is responsible for the smooth operation of the Collaboration [37]. Here we summarize the PI's work at this unique time in the Collaboration's history as we make the transition to CLAS12 operations.

The CLAS charter prescribes the procedure for internal, *ad hoc* reviews of papers for publication. The PI managed partial or full *ad hoc* reviews for 26 papers during his two-year tenure. He was also responsible along with the Physics Working Group chairs to organize internal reviews of new proposals in preparation for the PAC meetings each summer. Finally, the chair has the primary responsibility for organizing the three Collaboration meetings held each year. This involved recruiting plenary speakers and dealing with issues raised by the membership.

There was a variety of issues that arose over the last two years. We had to decide how to handle Collaboration members still interested in analysis of previous CLAS6 results, but not able to participate in CLAS12 operations. We now use the existing limited membership for them [37]. The PI organized a series of committees to ensure a smooth transition to CLAS12 operations. The Common Tools Committee assessed and guided the software development for simulation, reconstruction, and analysis of the data so that we are ready when beam arrives [38]. The Analysis Committee of Experts (ACE) was formed from senior members of the Collaboration who had considerable experience with CLAS6 to review all the procedures needed to enable full and complete analysis when production running starts. This committee has held 22 meetings since February, 2017 and produced a draft document to guide the Collaboration. In the CLAS6 era, an analysis review committee was usually formed after data-taking and the analysis were complete. To speed this process we formed the analysis review for the first production run (scheduled for early 2018) in July, 2017. The idea is to get the procedures and plans approved beforehand so that when the data arrive the analyzers will have a clearer picture of what has to be done.

Scheduling has become an issue in the Collaboration because of an overabundance of excellent physics proposals approved by the PAC. The Collaboration has organized itself into ten run groups around different sets of running conditions. The PI initiated a meeting of the run group leaders to get feedback on early, tentative beam scheduling and to elicit ideas for more efficient use of CLAS12. That discussion continues.

The PI has completed a draft of a CLAS Chair manual to document the routine tasks required of the chair [39]. He has also volunteered to act as post-chair for the first nine months of the new chair's tenure. This step enabled the PI to complete the chair manual, and to manage a portion of the *ad hoc* reviews still active. We also note here that first beam in CLAS12 was in February, 2017 when the successful Key Performance Parameter (KPP) run was performed.

2.1.4 Out-of-Plane Structure Functions of the Deuteron

We are investigating the out-of-plane structure functions of the deuteron using the $^2\mathrm{H}(\vec{e},e'p)n$ reaction in CLAS6 to establish a baseline for the hadronic model of nuclei. This project is far along and we have a draft analysis note undergoing internal, Collaboration review. The major technical issues have been addressed including revisions to the method for comparing the theoretical calculations with the measured asymmetry. There are significant organizational issues with the paper that remain. However, with the imminent start of production runs in early 2018 and the need to make progress on the SVT alignment and the CLAS Chair duties this project has been on hold for the last two years. We will pick up the thread of this work in the next grant period.

2.1.5 Other Projects

The PI also supported a Richmond undergraduate at JLab. David Brakman is a computer science/physics major who lives in Newport News. In the summers of 2015 and 2016 he joined the JLab electronics group under the direction of Mr. Chris Cuevas to work on controls software for cryo-targets [40, 41]. In both summers he was supported by this grant.

In summary, the Richmond group continues to prepare for the G_M^n experiment by developing simulations for all aspects of the experiment. We are also making significant contributions to other preparations for the CLAS12 era beyond G_M^n. The geometry and alignment of the SVT is necessary so it reaches its design specifications. Our Richmond undergraduates and Surrey masters students continue to contribute to the project. The PI spent two exciting years as Collaboration chair at a crucial time in the Collaboration's history as we enter the CLAS12 era.

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.

JLab is a unique tool for basic research in nuclear physics. The central instrument is the Continuous Electron Beam Accelerator Facility (CEBAF); a superconducting electron accelerator with a maximum energy of 12 GeV, a 100% duty cycle, and a maximum current of $\approx 85\ \mu$A. JLab has completed the 12 GeV Upgrade project to double the beam energy, enhance the existing experimental halls, and construct a new detector in Hall D (see left-hand panel in Figure 4). CLAS12 in Hall B is a large particle detector with a toroidal, multi-gap magnetic spectrometer

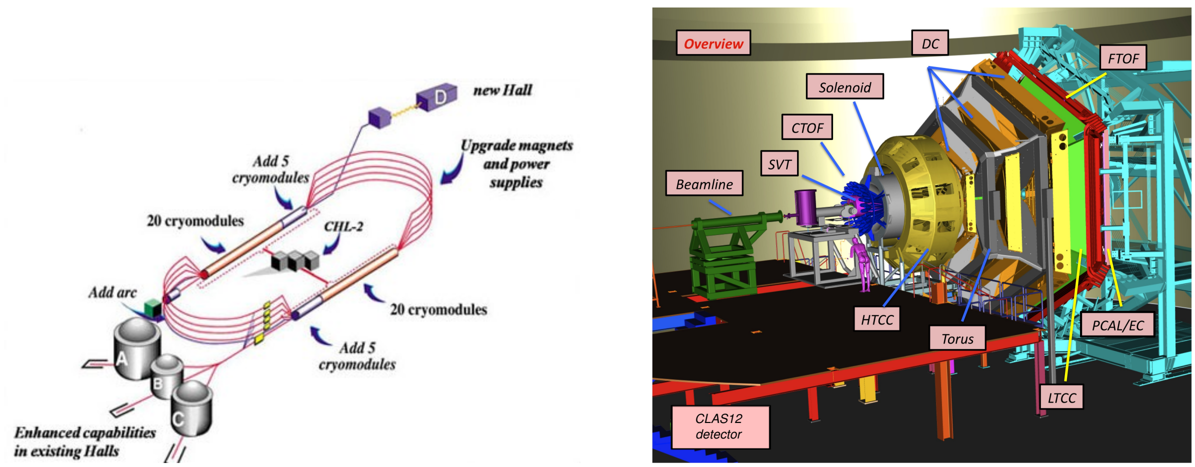

Figure 4: CEBAF layout (left) and CLAS12 design drawing (right).

with nearly full solid angle coverage at forward angles (the Forward Detector) and a large solenoid centered on the target for large angles (the Central Detector). See the right-hand panel in Figure 4. There are over 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 [42] to measure charged particle trajectories, Cerenkov detectors [43] to identify electrons, pions, and kaons, scintillators [44] for time-of-flight measurements, and electromagnetic calorimeters [45]. 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 for particle detection. The Richmond group has been part of the CLAS Collaboration since its inception.

Our focus for the next three years is on preparations for the start of operations of the CLAS12 detector, its commissioning, and production running. In this section we will describe our program on (1) the G_M^n measurements in Halls A and B (emphasis on Hall B), (2) alignment of the Silicon Vertex Tracker (SVT) in the Central Detector, (3) the analysis of the fifth structure function with existing CLAS6 data, (4) our participation 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 nonperturbative region [16]. 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 [16, 17, 18, 19, 20]. We are part of a broad campaign to measure the four elastic nucleon form factors (electric and magnetic ones each for the proton and neutron) at JLab that include seven experiments approved for running [20, 46].

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 [22]. He is also a co-spokesperson on a Hall A measurement of G_M^n E12-09-019. For the next budget period our focus will be on the CLAS12 experiment. We propose to develop software for simulating the CLAS12 detector and analyzing the results. The JLab management and the CLAS Collaboration recognize that we must be ready to collect, calibrate, and analyze data from CLAS12 at start-up to produce physics results in a timely manner [10, 11, 12, 13, 14]. The projects we describe below are aimed at both preparing for E12-07-104 and fulfilling this Collaboration and Laboratory goal.

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 [47, 48].

$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n \qquad \text{and} \qquad F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p \tag{1}$$

The result of this flavor decomposition is shown in the left-hand panel of Figure 5 [47]. There are

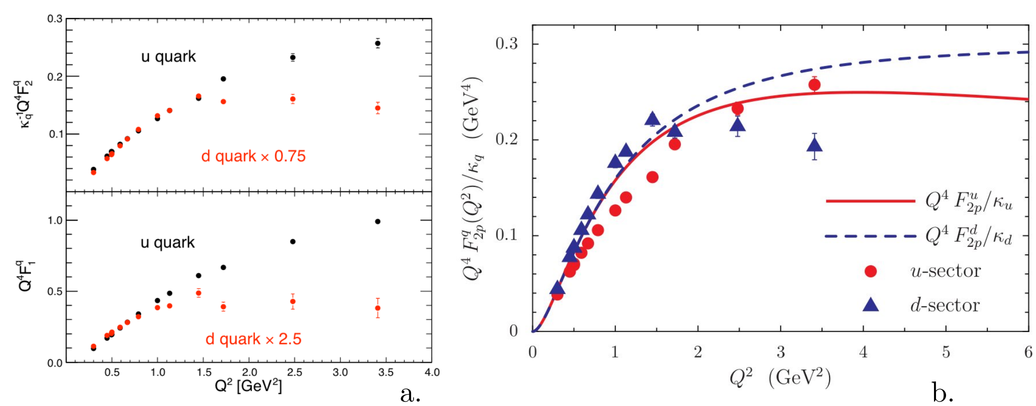

Figure 5: Flavor decomposition of the nucleon elastic form factors showing (a) the Q^2 behavior of the Dirac and Pauli form factors for the $u-$ and $d-$quarks and (b) an NJL calculation of the data [47, 49]. The form factors are multiplied by Q^4 to show their properties more clearly.

large differences between the u- and d-quark distributions both in size and shape. The u-quark form factors in Figure 5 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 perturbative QCD to follow a $1/Q^2$ form (Figure 1 in Reference [47]). This feature differs sharply from the results for the individual quarks in Reference

[47]. These data have opened a new window into the nucleus. One example of what we can learn is shown in Figure 5b. Flavor form factors are calculated using the NJL model with the empirical nucleon form factors and treating the pion degrees of freedom as a perturbation on the quark core [49]. The quark form factors are extracted assuming charge symmetry. No model parameters are adjusted to fit the data and the agreement is encouraging. Diquark correlations arise naturally in this model and may provide an explanation of the $u-$ and $d-$quark Q^2 dependence in Figure 5. A variety of other calculations vary widely in their predictions for the EEFFs [50, 51].

The elastic form factors for both the proton and neutron are an important, early test case of the accuracy of the lattice calculations. With all four of them, one can extract the isovector combination of the form factors [52] which are easier to calculate on the lattice because they lack disconnected contributions [22]. We also expect to obtain a new, unprecedented tomographic view of the interior of the nucleons through measurement of generalized parton distributions (GPDs). The elastic form factors are a limiting case of the GPDs and provide a vital constraint on GPD models [53]. Lattice QCD calculations are now becoming feasible in the few-GeV^2 range, and over the next decade these calculations will become increasingly precise [54]. There is a great opportunity here for discovery.

The physics reach of the G_M^n measurement is shown in Fig 6. The reduced form factor $G_M^n/\mu_n G_D$ is plotted versus Q^2 where G_D is the dipole form factor $G_D(Q^2) = 1/(1+Q^2/\Delta)^2$ and $\Delta = 0.71$ GeV^2. A selection of the world's data is shown by the open, green squares. The CLAS6 G_M^n measurement is shown by the open, red circles [1]. The anticipated results for E12-07-104 are shown in the closed, black squares. The bar graphs show the measured (CLAS6 in red) and anticipated (CLAS12 in black) systematic uncertainties. The E12-07-104 measurements will reach out to $Q^2 \approx 13$ (GeV/c)^2, more than doubling the range of the high-precision measurements. The anticipated Hall A results are the blue, open squares and will extend the high-statistics measurement out to $Q^2 = 13.5$ GeV^2 though in larger steps. The two theory curves illustrate different attempts to describe the data: a constituent quark model using the light-front formalism (long-dashed curve from Miller [62]) and a calculation based on the Dyson-Schwinger equation (dashed curve from Cloet *et al.* [63]). The calculations diverge for $Q^2 > 5$ (GeV/c)^2; above the range of nearly all the existing data. The planned G_M^n measurement will have the precision to distinguish between them.

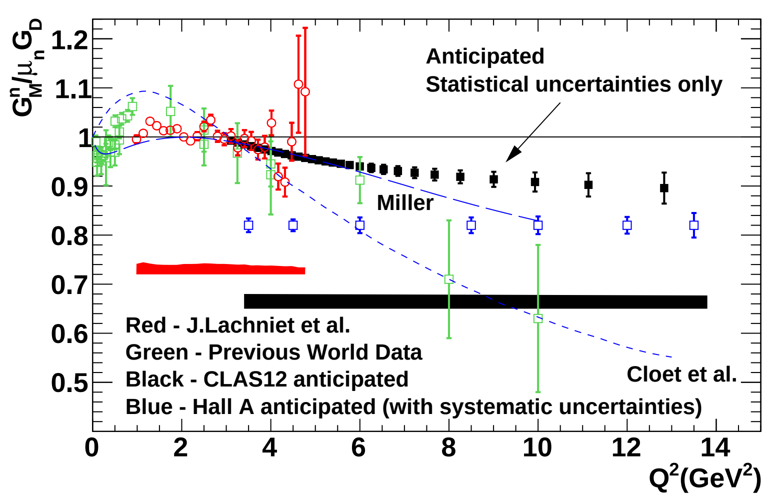

Figure 6: Results for $G_M^n/(\mu_n G_D)$ from CLAS6 (red), previous data (green) [55, 56, 57, 58, 59, 60, 61], theoretical calculations, and expected data from CLAS12 (black) are shown.

To measure G_M^n we use the ratio R of $e-n$ to $e-p$ quasielastic (QE) scattering from a deuterium target (there are no free neutron targets). We will use the same method in the CLAS12 measurement that was used in the CLAS6 one [1]. The differential cross section for elastic electron-nucleon scattering can then be calculated in the lab frame as [64]

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

where σ_{Mott} is the cross section for scattering from a point particle, G_E is the electric form factor,

G_M is the magnetic form factor, $\tau = Q^2/4M^2$, 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

$$R = \frac{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'n)p\right)_{QE}}{\frac{d\sigma}{d\Omega}\left({}^2\mathrm{H}(e,e'p)n\right)_{QE}} = a(E,Q^2)\frac{\frac{{G_E^n}^2+\tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2\tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2+\tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2\tan^2(\frac{\theta}{2})} \tag{3}$$

where E is the beam energy and $a(E,Q^2)$ corrects for nuclear effects which can be calculated from deuteron models and is close to unity at large Q^2. To select QE events we require θ_{pq}, the angle between the detected nucleon and 3-momentum transfer $\vec{q}$ to be small which eliminates most inelastic events near the QE peak [1]. This technique can be applied equally well to both proton and neutron events - reducing biases in the analysis by using the same method for both nucleons. By taking the ratio R we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction and trigger efficiencies, the deuteron wave function, and radiative corrections [1, 65, 66]. The extraction of G_M^n depends on our knowledge of the other three nucleon form factors, but the proton form factors are precisely known (the denominator in Equation 3 is essentially the measured proton cross section) and the neutron's electric form factor G_E^n is typically small so its impact on the systematic uncertainty is limited. This technique does require precise knowledge of the neutron detection efficiency (NDE) and careful matching of the neutron and proton acceptances. To measure the neutron detection efficiency we proposed a unique dual-cell, co-linear, liquid-hydrogen-liquid-deuterium target [5, 21]. The $ep \to e'\pi^+ n$ reaction is a source of tagged neutrons which are detected in two, overlapping measurements with both the electromagnetic calorimeter (EC) and the forward time-of-flight (FTOF) system - providing a powerful consistency check on the measurements. By using the dual target we can measure the NDE under the same running conditions as the production data reducing our vulnerability to changes in electronics thresholds and gains and detector performance. To measure the proton detection efficiency we use elastic ep scattering on the hydrogen target. Acceptance matching is done event-by-event by detecting the electron, assuming QE scattering, and calculating the trajectory for both proton and neutron. If both particles are expected to strike the active area of the detector, we continue with the analysis, otherwise the event is rejected [1, 7, 8, 65]. Corrections for nucleon Fermi motion in the deuteron are simulated. The methods described here were successful in our previous analysis of the CLAS6 E5 data [1].

For the CLAS12 G_M^n experiment we need an additional requirement to control the inelastic background. At higher Q^2 the width of inelastic scattering increases and encroaches on the quasielastic region. The left-hand panel in Figure 7 shows this effect along with the much greater inelastic cross section relative to the QE events. The red histogram is from QE events, the green one is from inelastic events, and the blue one is their sum.

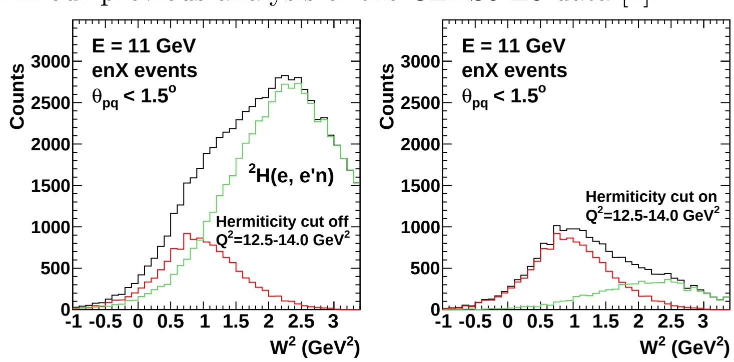

Figure 7: Effect of hermiticity cut in the highest Q^2 bin where the inelastic contamination is greatest.

We can remove most of this background by applying cuts on proton and neutron angles relative to $\vec{q}$ (θ_{pq} in Figure 7) to select QE events and reject inelastic ones that produce additional particles in the final state. The large, solid-angle coverage of CLAS12 for this final, hermiticity cut is crucial. The result is shown in the right-hand panel of Figure 7 showing most of the inelastic background has been removed.

Here we discuss the beam schedule at JLab for the next grant period. This discussion is based on the current experimental schedule [67] and planning done by the Hall leaders. We note this is all tentative and the schedule after 2018 is subject to many constraints. The upcoming CLAS12 experimental schedule begins with the engineering run to commission the detector in December, 2017. In early 2018 we begin running on a proton target for two extended periods, spring and fall, concluding in December 2018. The current schedule ends at that point. We have joined Run Group A (RG-A) which is responsible for managing the run period to support the alignment of the SVT. We are part of the team calibrating and aligning the SVT to reach its design specifications (see Section 2.1.2). We will also study the $^1\mathrm{H}(e, e'\pi^+n)$ which is the source of tagged neutrons in the NDE measurement for the G_M^n experiment. This participation will enable us to test our analysis codes on real data [4, 6]. The CLAS Collaboration has a very tentative schedule further into the future. On this schedule, after the proton experiment we will run on a deuterium target in Run Group B (RG-B) - creating the possibility of collecting data for the G_M^n experiment. A High-Impact experiment entitled "DVCS on the Neutron with CLAS12 at 11 GeV" is driving many of the running conditions including the total beam exposure on the deuterium target so the dual $LH_2 - LD_2$ may not be used in RG-B. The event rate in CLAS12 is limited by the background rates in the Forward Detector so the planned dual-target for the G_M^n experiment would reduce the total beam exposure on deuterium. This could mean that the G_M^n experiment runs later, but in the interim we will investigate other ways to measure the NDE within the constraints of RG-B (see below). On the other hand, the Hall A measurement of G_M^n appears to be on track to take data in the next 2-3 years.

Accurate measurement of the NDE is key to the expected precision of the G_M^n experiment [68]. Comparison of past measurements at different laboratories reveals considerable tension among those experiments presumably due to variations in detector performance and efficiency. The dual $LH_2 - LD_2$ target mitigates those effects by collecting the NDE data *in situ* at the same time and with the same detector as the production data on deuterium. A design of the target is in hand and a simulation has been developed [3, 23]. See Section 2.1.1. During the period of this proposal we will study the impact of the target on background rates, elastic and inelastic scattering data quality, vertex resolution (so we can separate events from the two targets), and other effects. We must also submit the design to a readiness review to use the target in CLAS12.

If Run-Group B uses a deuterium-only target we will examine alternatives to the dual target to see if adequate precision can be achieved with other calibration reactions. The quasielastic $^2\mathrm{H}(e, e'pn)$ reaction could be used. Similar to the $^1\mathrm{H}(e, e'\pi^+n)$ reaction, 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 [69, 70]. The question we have to answer is what will be the likely precision of the NDE using this new reaction. With the dual target we expect a contribution of about 1% to the systematic uncertainty in the ratio R measurement. In the CLAS6 G_M^n measurement we saw a systematic uncertainty of about 1-1.5%. 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 that is now undergoing CLAS Collaboration review. It is an intriguing possibility, but the current 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. Our plan is to simulate both reactions to see if we can take advantage of the deuterium running in Run Group B.

To summarize this portion of the renewal proposal, the motivation for the G_M^n measurement remains strong and we continue to develop the codes and algorithms for analyzing that data when it arrives. It is a widely held goal of the CLAS Collaboration that full end-to-end simulations of the analysis chain for a reaction should be in-hand before the run begins. There is still considerable uncertainty with the experiment schedule, but there is a possibility of running on deuterium in 2019, however it may be without the dual target needed to make the *in situ* measurement of the neutron detection efficiency. Hence, we will investigate alternatives that have been considered in other approved experiments to measure the NDE.

2.2.2 Geometry and Alignment of the Silicon Vertex Tracker

We are part of the team developing software for CLAS12 in preparation for the start of experimental running in 2018. The goal is to be ready to analyze data when beam arrives [10, 11]. The computing requirements for CLAS12 are large and for the Collaboration to successfully analyze data at startup requires accurate, adaptable, and efficient code. We are developing software to simulate and analyze data from the Silicon Vertex Tracker (SVT) to model the geometry and align the components.

We are responsible for the SVT geometry package that is used by the CLAS12, physics-based simulation *gemc* and the Common Tools reconstruction. The parameters needed for the package are stored in the CLAS12 Constants Database (ccdb). The package was first developed during the current grant period and was the subject of a Surrey masters thesis, a CLAS12-NOTE ([32]) and a poster at the fall, 2016 Division of Nuclear Physics conference ([33]). See Section 2.1.2 for more details. We will continue our involvement during the period of the proposed grant as the software is used in the coming engineering run and first production runs.

Reaching the CLAS12 design specifications requires understanding the geometry of the detector components as they are built and installed and during their operation. Differences between the nominal geometry and the detector built in Hall B can degrade the resolution and lead to biases that could effect the physics. Our focus here will be on track-based alignment as opposed to complementary tasks like surveying. The alignment is important for the G_M^n experiment (Sections 2.1.1 and 2.2.1). In the dual-cell target the liquid hydrogen and deuterium cells may only be 1 cm apart (see Figure 1) requiring the resolution in the z position of the scattered electron vertex to meet the design specification of 1 mm.

To align CLAS12 we start by considering a least-squares approach (also known as the closed-form method). The parameters of a fitted track are correlated with positions of the detector components. Consider the SVT. If the region closest to the target (Region 1) is offset during installation so the azimuthal position of a module is shifted by a few tenths of a degree (see Figure 3a for a view of the $x-y$ plane of the SVT), then a track will generate a different set of hits than one would obtain with the nominal geometry. The displaced region will have a biased, nonzero average residual, but so will the adjacent regions making it ambiguous how to adjust the detector positions to obtain the correct azimuthal angle ϕ of the track.

In the least squares approach a fit is made simultaneously to all the track parameters and the geometry parameters enabling the process to capture correlations among the parameters. However, for a detector like CLAS12 the number of detector parameters is large so the computational demands may be prohibitive. A solution to this is the program Millepede II optimized for fits (based on χ^2 minimization) to large numbers of parameters [34, 35, 36]. The method takes advantage of the difference between local parameters (fit parameters for individual tracks which vary event by event) and global ones (the positions, orientations, deformations, *etc* of the detector components which should be the same from event to event). The difference between these parameter types manifests itself in the structure of the least squares matrix so all the information from the local (track) fits can be included in the matrix that contains the global (detector) parameters - significantly decreasing the size of the problem. This matrix equation is then solved by inversion and the inverse matrix is the covariance matrix of the global parameters. Fits with as many as 100,000 global parameters are possible [36]. The price one pays for reducing the size of the problem is that the user has to proved additional information to the code - the partial derivatives of the residuals with respect to the local fit parameters and the global geometry parameters.

The analysis chain to extract the geometry misalignments is shown in Figure 8. Starting on the

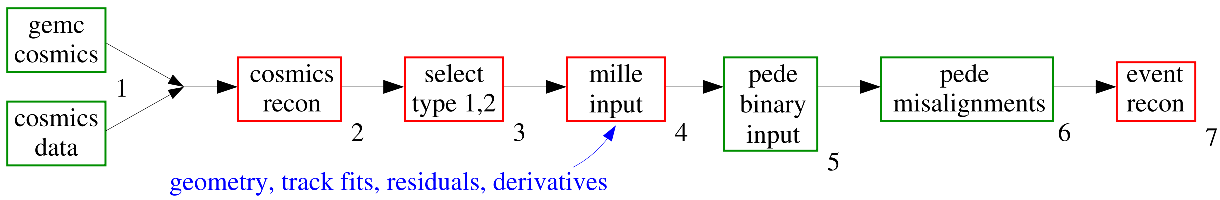

Figure 8: Analysis chain using `millepede` to extract misalignments from the CLAS12 SVT. Red boxes are codes written in Java while green represent C^{++} programs.

left, (1) cosmic rays (from the *gemc* simulation or real ones) from the SVT are (2) reconstructed using the Common Tools and (3) the results passed to a groovy script that selects different event types. The red boxes in Figure 8 are written in Java, green are written in C^{++}. Type-1 events have six or eight crosses where a cross is a vector formed from the clusters of hits in the two silicon layers of a sector. The number of crosses depends on the SVT configuration. The original setup had four regions, but will have only the first three regions in the final configuration (along with micromegas trackers). For type-1 events the crosses all lie on the horizontal modules. See Figure 3a. Type-2 events also have six or eight crosses, but none are required to be one of the horizontal modules. (4) In the next step the selected events are processed again and the information needed to run `millepede` is gathered from the reconstruction or generated in the code. In addition to the reconstruction data (*i.e.* the track fit parameters), the code requires the endpoints of each silicon strip in the event, the residual, and the partial first derivatives of the global and local parameters. These data are collected for each event and written out into a text file. (5) This file is used as input to the first of two codes that form the `millepede` program. The first code `mille` reads the text file and produces another, binary file containing the input in a format readable by the next program in this process named `pede`. (6) The `pede` code is where the actual least squares fitting occurs using the first derivatives calculated by the user in (4). It produces a set of misalignments for the global parameters. This misalignments are then loaded into the CLAS12 offline database (`ccdb`) and can be applied as shifts to the reconstruction geometry using the SVT geometry code [32, 33]. A discussion of the current status of this project is in Section 2.1.2 and some results are shown in Figure 3.

Our Plan of Work for this part of the proposal is three-fold. (1) We will extend the existing code to include type-2 events. There are more of these events in our cosmic ray samples than the type-1 events and they illuminate more of the modules in the SVT where the type-1 events only illuminate the horizontal ones. The type-2 events require the same number of modules as the type-1 events (recall Figure 3). We calculate the distance-of-closest-approach (DOCA) between the cosmic ray and a silicon strip on the SVT and along the face of the sensor. This is a comparatively routine geometry calculation requiring the slopes and intercepts defining the cosmic-ray track and the endpoints of the silicon strip as input. To use `millepede` one must now take the derivative of this formula for the DOCA with respect to each of those parameters. These derivatives are extremely complex and probably can't be reliably done by humans. We use *Mathematica*. The DOCA can be defined symbolically in *Mathematica*, the derivative taken with respect to the desired variable, and the result exported in C^{++} format into a file. The C^{++} syntax can be readily converted to Java syntax. The formulas for the derivatives used in step 4 of Figure 8 have character counts that ranged from 11,000 to 25,000. The code to analyze the type-2 events has been written and successfully tested on a sample of type-1 events. Testing and validation on a type-2 sample will be forthcoming. (2) The next step will be to study events that originate from the target. This will be done initially in simulation and then with real data when beam arrives in CLAS12. (3) We will explore the impact of varying different parameters to find which ones are sensitive (or insensitive) to changes in the geometry.

As the analysis develops this project will consider different avenues of research. The studies so far have been with straight tracks with the magnetic field of the solenoid in the Central Detector set to zero. Eventually we should be able to apply the `millepede` algorithm to helical tracks for non-zero magnetic fields which will open up opportunities to calibrate and monitor the performance of the SVT during production runs. The Central Detector has the SVT and micromegas to provide tracking. These two systems will have to be integrated in the `millepede` program so we can take full advantage of the two tracking sub-systems.

2.2.3 Out-of-Plane Structure Functions of the Deuteron

We have made preliminary measurements of the quasielastic (QE), out-of-plane, structure functions of the deuteron (the fifth structure function) in the GeV region to test the hadronic model of nuclei. The hadronic model of nuclear physics has been successful at low Q^2, but it is not well-developed in the GeV region even though we expect it to be valid there. There are few data to challenge theory - only three measurements for QE events, all at lower Q^2 [71, 72, 73]. The analysis is far along and a draft analysis note is under internal, Collaboration review. The project has been delayed because of the urgency of preparations for the start of CLAS12 running and the PI's duties as Collaboration Chair. In the next grant period we will work to complete the CLAS Analysis Note.

2.2.4 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and its understanding is a central challenge in nuclear physics. We will investigate the nature of confinement by studying the hadronization process across a wide range of nuclei. This will enable us to extract the quark production times (*i.e.*, the lifetime of a bare, struck quark) and the hadron formation times (*i.e.* the time for a hadron to become fully dressed with its gluon field). Experiment E12-06-117 was approved by PAC30 and earned a scientific rating of A^- from PAC36 in 2010 [74]. Gilfoyle is a co-spokesperson on the proposal and is responsible for analysis of the π^0, η, and η' channels along with K. Joo from the University of Connecticut. During the period of this grant we will continue work on the simulation of events in CLAS12.

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 preparations for the start of data taking in CLAS12 and the CLAS12 G_M^n measurement. Our focus is on developing software for simulation 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 usually have graduate students. The proposed masters student would be part of a joint program between Richmond and the University of Surrey in the UK. Undergraduate physics majors at Surrey normally graduate in three years, but some apply and are selected to receive a masters degree in physics that includes a year of research. These are the students who would be funded by this program. In physics skills they are equivalent to first-year graduate students in the US. The program director at Surrey, Prof. P. Regan, is enthusiastic about the opportunity for their masters students to work at JLab (see link to letter from Dr. Regan in Reference [75] and Appendix A). We request funds only for an annual stipend; there are no tuition costs.

We have thought carefully about how to structure this student's experience. (1) We would station the person in the Richmond office at JLab. Gilfoyle routinely travels to JLab (see Section 2.5); he spends about 60 days each year on site so there would be ample time for for collaboration. He is an active member of the CLAS12 Software group which provides a good working environment and community to work in. Three JLab staff scientists (Ziegler, Gyurjyan, Ungaro) in the group are committed to supporting this student. (2) The program proposed here covers a significant range of topics from analysis of data to developing new tools for CLAS12. We will work closely with the our collaborators to match the students' skills and interest to the needs of the program.

We received funding for two, ten-month, masters students in the current grant period for 2016 (Mr. Peter Davies) and 2017 (Mr. Charles Platt). Mr. Davies developed the geometry model of the SVT and the associated methods now in standard use in the Common Tools. His thesis was published as a CLAS-NOTE [32]. In 2017 Mr. Charles Platt's project is focused on testing, updating, and validating the geometry code and integrating it with the reconstruction code. His research year concludes in December, 2017. In the previous grant period (2012-2015) we received funding for one masters student (Mr. Alex Colvill) through a supplemental grant request. He developed the first version of the stand-alone reconstruction code for the CLAS12 time-of-flight subsystems - adapting the existing Fortran-based, CLAS6 code to the current service architecture using the Java language. His thesis was later adapted to CLAS12-NOTE 2014-003. A letter of support for this program from Dr. V.Ziegler (CLAS12 Software Group leader) is in Reference [76] and Appendix B. This is an exciting time at JLab and the program outlined here would embed the student in that community and provide abundant opportunities for working with the PI.

It is worth mentioning this collaboration with Surrey has been a success in the nuclear structure community at Yale, Kentucky, Florida State, Notre Dame, LBL, and even Richmond (through a faculty colleague, Dr. Con Beausang). Those programs benefited from the Surrey students and many of them have gone on to US graduate schools, enhancing the US workforce.

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. Three from our lab are currently staff scientists at NASA-Goddard, NASA-Huntsville, and the Jet Propulsion Laboratory, one is a faculty member at Stanford, and one is a researcher at Cornell in biological physics. Among students who worked in our laboratory over the last nine years two (Sherman, Mark Moog) went to doctoral programs in physics (Old Dominion and Chapel Hill, respectively), another (Matt Jordan) is in graduate school in electrical engineering at Georgia Tech, Calina Copos is a graduate student in applied mathematics at UC, Irvine and Justin Ruger is pursuing a doctorate in nuclear physics at Catholic University. 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, attend collaboration meetings, present their work at group meetings and at local, national, and international conferences [3, 4, 5, 6, 7, 8, 30, 33, 77, 78, 79, 80, 81, 82], and are co-authors on technical reports [23, 29, 83, 84, 85]. In the last three years six different students worked in my laboratory including a former high school student who was a physics major at Richmond and is now pursuing a doctorate in physics at Old Dominion. They were funded by a mixture of DOE grant and University funds.

2.5 Institutional Support and Resources

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 [86]. An array of student workstations is used for software development and non-CPU-intensive tasks all in the Physics Department research area. This cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can sit in the JLab queue more than a day before submission. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm. The University information technology staff maintains the cluster.

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

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

2.6 Summary

We now summarize our Plan of Work for the next grant period. Our research is centered on the medium energy program at Jefferson Lab, in particular on the upcoming measurement of the neutron magnetic form factor G_M^n with CLAS12. We will test and validate the end-to-end simulation of the G_M^n experiment we have developed and study the calibration reactions for measuring the neutron detection efficiency with and without the dual $LD_2 - LH_2$ target. We are also committed to the developing software for the simulation, reconstruction, and analysis of data from CLAS12. We will continue to support, test, and validate the SVT geometry code developed by our group. Aligning the SVT will be a major focus with the start of production running in CLAS12 in 2018.

We will revive the study of the fifth structure function now that the PI is no longer CLAS Collaboration Chair and continue to contribute to software planning and the Time-of-Flight software development. 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 in 2018 and the possible running of the G_M^n experiment in Hall A. By far the largest volume of data generated by an experiment is the raw data containing the digitized readout from the data acquisition system. However, the raw data is only meaningful in the context defined by the metadata 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

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

1. P. Collins et al. Photon beam asymmetry Σ in the reaction $\vec{\gamma}p \rightarrow p\omega$ for $E_\gamma = 1.152$ to 1.876 GeV. *Phys. Lett.*, B773:112–120, 2017.

2. P. T. Mattione et al. Differential cross section measurements for $\gamma n \rightarrow \pi^- p$ above the first nucleon resonance region. *Phys. Rev.*, C96(3):035204, 2017.

3. D. Ho et al. Beam-Target Helicity Asymmetry for $\vec{\gamma}\vec{n} \rightarrow \pi^- p$ in the N^* Resonance Region. *Phys. Rev. Lett.*, 118(24):242002, 2017.

4. E. L. Isupov et al. Measurements of epe+p cross sections with CLAS at 1.40 GeV<W<2.0 GeV and 2.0 GeV^2 < Q^2 < 5.0 GeV^2. *Phys. Rev.*, C96(2):025209, 2017.

5. D. Rimal et al. Measurement of two-photon exchange effect by comparing elastic $e^{\pm}p$ cross sections. *Phys. Rev.*, C95(6):065201, 2017.

6. I. Bedlinskiy et al. Exclusive η electroproduction at W > 2 GeV with CLAS and transversity generalized parton distributions. *Phys. Rev.*, C95(3):035202, 2017.

7. P. Collins et al. Photon beam asymmetry Σ for η and η' photoproduction from the proton. *Phys. Lett.*, B771:213–221, 2017.

8. P. E. Bosted et al. Target and beam-target spin asymmetries in exclusive pion electroproduction for $Q^2 > 1$ GeV^2. II. $ep \rightarrow e\pi^0 p$. *Phys. Rev.*, C95(3):035207, 2017.

9. M. Mayer et al. Beam-target double-spin asymmetry in quasielastic electron scattering off the deuteron with CLAS. *Phys. Rev.*, C95(2):024005, 2017.

10. P. E. Bosted et al. Target and Beam-Target Spin Asymmetries in Exclusive Pion Electroproduction for $Q^2 > 1$ GeV^2. I. $ep \rightarrow e\pi^+ n$. *Phys. Rev.*, C95(3):035206, 2017.

11. A. Kim et al. Target and double spin asymmetries of deeply virtual π^0 production with a longitudinally polarized proton target and CLAS. *Phys. Lett.*, B768:168–173, 2017.

12. X. Zheng et al. Measurement of Target and Double-spin Asymmetries for the $\vec{e}\vec{p} \rightarrow e\pi^+(n)$ Reaction in the Nucleon Resonance Region at Low Q^2. *Phys. Rev.*, C94(4):045206, 2016.

13. R. Dickson et al. Photoproduction of the $f_1(1285)$ Meson. *Phys. Rev.*, C93(6):065202, 2016.

14. P. E. Bosted et al. Target and beam-target spin asymmetries in exclusive π^+ and π^- electroproduction with 1.6- to 5.7-GeV electrons. *Phys. Rev.*, C94(5):055201, 2016.

15. C. A. Paterson et al. Photoproduction of Λ and Σ^0 hyperons using linearly polarized photons. *Phys. Rev.*, C93(6):065201, 2016.

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

1. I. Senderovich et al. First measurement of the helicity asymmetry E in η photoproduction on the proton. *Phys. Lett.*, B755:64–69, 2016.

2. N. Guler et al. Precise determination of the deuteron spin structure at low to moderate Q^2 with CLAS and extraction of the neutron contribution. *Phys. Rev.*, C92(5):055201, 2015.

3. H. S. Jo et al. Cross sections for the exclusive photon electroproduction on the proton and Generalized Parton Distributions. *Phys. Rev. Lett.*, 115(21):212003, 2015.

4. M. E. McCracken et al. Search for baryon-number and lepton-number violating decays of hyperons using the CLAS detector at Jefferson Laboratory. *Phys. Rev.*, D92(7):072002, 2015.

5. N. Zachariou et al. Determination of the beam-spin asymmetry of deuteron photodisintegration in the energy region $E = 1.1$ - 2.3 GeV. *Phys. Rev.*, C91(5):055202, 2015.

6. S. Pisano et al. Single and double spin asymmetries for deeply virtual Compton scattering measured with CLAS and a longitudinally polarized proton target. *Phys.Rev.*, D91(5):052014, 2015.

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

1. P. Davies†, V. Ziegler, M. Ungaro, Y. Gotra, A. Kim, and G.P. Gilfoyle, "Geometry and Alignment Software for the CLAS12 Silicon Vertex Tracker", CLAS-NOTE 2017-008, Jefferson Lab, 2017.

2. G.P. Gilfoyle, R. De Vita, B. McKinnon, K.Hicks, and D.Ireland, "CLAS Collaboration Chair Procedures", CLAS-NOTE 2017-015, Jefferson Lab, 2017.

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

1. G.P. Gilfoyle, "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab", submitted to the Proceedings of the 47th International Symposium on Multiparticle Dynamics (ISMD2017), EPJ Conferences Proceedings, 2017.

2. A.Balsamo*, 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).

3. K. Sherman* and G.P.Gilfoyle, "Measuring the Neutron Detection Efficiency in CLAS12", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00047 (2016).

4. A.Balsamo*, K.Sherman*, and G.P.Gilfoyle, "Measuring Quasi-Elastic e-n and e-p Scattering from Deuterium", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00046 (2016).

5. P.Davies* and G.P.Gilfoyle, "Geometry Calibration of the SVT in the CLAS12 Detector", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00045 (2016).

6. G.P. Gilfoyle, "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab", Presented at Electromagnetic Interactions in Nucleons and Nuclei 2015, Paphos, Cyprus, Nov 3, 2015.

7. K. Sherman and G.P.Gilfoyle, "Study of the Neutron Detection Efficiency for the CLAS12 Detector", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00122 (2015).

8. O. Alam and G.P.Gilfoyle, "Dual Target Design for CLAS12", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00121 (2015).

9. D. Brakman, C. Cuevas, and G.P.Gilfoyle, "Cryotarget Control Software for Liquid Deuterium", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00039 (2015).

10. D. Brakman, C. Cuevas, and G.P.Gilfoyle, "Uniformly Rastering an Electron Beam on a Polarized Cryotarget", Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00043 (2016).

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

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
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.
Summer, 1988 - Visiting Research Professor, University of Pennsylvania.
1987-1993 - Assistant Professor, University of Richmond.
1985-1987 - Postdoctoral Research Fellow, SUNY at Stony Brook.

Research and Teaching Grants
1990-present - US Department of Energy ($1.7M in ten awards).
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. D. Rimal et al. (CLAS Collaboration), "Measurement of two-photon exchange effect by comparing elastic $e^{\pm}p$ cross sections". Phys. Rev., **C95** 065201 (2017).

2. N. Guler et al. (CLAS Collaboration), Precise determination of the deuteron spin structure at low to moderate Q^2 with CLAS and extraction of the neutron contribution. *Phys. Rev.*, C92(5):055201, 2015.

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. "Hall B Organization", CLAS12 Ready-for-Science Review, Jefferson Lab, September 25, 2017.

2. "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors (G_M^n) at Jefferson Lab", 47th International Symposium on Multi-Particle Dynamics, Tlaxcala City, Mexico, Sep 12, 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, 2017	Gilfoyle/Regan
C. Platt	Feb, 2017	Feb, 2017	Masters	Expected June, 2017	Gilfoyle/Regan

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	$231,000
Effort	63 person months over three years

By the end of this funding period (5/31/2018) we expect to have the following funds remaining in equipment, travel and undergraduate stipends shown in Table 2. An explanation is below.

	Grant	Item	Amount
1.	Current Grant	Supplies	$1,100
2.	Current Grant	Travel	$20,000
3.	Current Grant	Student Stipends	$7,300

Table 2: Remaining funds

Items 1-2. We have been able to use University funds over some the last three years to support travel and some equipment purchases. The PI held a University of Richmond endowed chair that provided annual funds for professional development. Using these funds for equipment and travel has enabled us to reduce our reliance on the DOE grant. Unfortunately, Gilfoyle's chair has a term limit which was reached in 2016 so those funds will no longer be available. In addition, the Chair duties reduced the PI's time for attending conferences.

Item 3. The University supports student summer research with stipends awarded on a competitive basis. My research students were especially successful over the last three years to obtain such funding from the University which has allowed us to add students to our group or extend the summer research of others. It is not clear that University support will be as forthcoming in the future, but the money here will ensure that I can support Alexander Balsamo next year. He has done considerable work on the end-to-end software chain for the G_M^n experiment and he is already committed to working for me next summer.

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

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.

Appendices

A Confirmation letter from the University of Surrey

Dr Gerard P. Gilfoyle
Clarence E. Denoon Jr. Professor of Science
Physics Department
University of Richmond
VA 23173
USA

Faculty of Engineering & Physical Sciences
Department of Physics
Guildford, Surrey GU2 7XH UK

Prof. P.H. Regan FInstP
NPL Professor of Radionuclide Metrology

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F: +44 (0)1483 686781
p.regan@surrey.ac.uk

22nd October 2017

Dear Dr. Gilfoyle,

On behalf of the Physics Department at the University of Surrey, UK, I am writing to express our full and continued support for your Department of Energy (DoE) research grant application in nuclear physics. This letter also confirms our strong desire to continue to place Surrey masters Master of Physics (MPhys) research students under your direct supervision at the University of Richmond and working at the Jefferson Laboratory. Beginning from our first mutual research student in 2013, all three MPhys student under your supervision, have all been a great successes from our point of view. The first two students graduated with the highest rated ('first-class') UK degree classification, thanks, in no small part to their assessed research project work, carried out under your supervision. (The third student will, as you know, return to Surrey for his final examinations in early 2018 and is also currently on track for to achieve first class honours).

The University of Surrey MPhys research programme is only available for those students on our physics major undergraduate masters programmes, and demands a level of academic achievement which matches the challenging condition given by the UK Research Council required to obtain a doctoral bursary funding. At the point when they begin their research placement, the MPhys students have achieved at least 300 academic university credits from taught courses laboratory work etc. While this is enough to obtain an ordinary bachelors degree (BSc), in the case of the Surrey MPhys programme, they do not exit at this stage, but rather obtain a further 180 academic credits in order to finally graduate with a masters (MPhys) degree. The Surrey MPhys program has now run for more than 20 years. The expectation is that the student is paid a salary/stipend by the host institution on the basis of them being a project-funded research student. In addition to placements within your group at UoR/J-lab, our students have undertaken successful research

Dr Gerard P. Gilfoyle
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B Support letter from Jefferson Lab

Jefferson Science Associates
Thomas Jefferson National Accelerator Facility

November 20, 2017

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 and was part of the CLAS12 software group when this Richmond/Surrey program at JLab was started. I am now leader of the CLAS12 software group.

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. That work is still going on.

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 Budget Justification

YEAR 1 (June 1, 2018 - May 31, 2019)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $18,000 whichever is smallest.

B.2 One masters student for four months (Feb-May, 2019) at an annual stipend of $29,500 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, 2018 - May 31, 2019 so the programs are out of phase. We expect a masters student to arrive by February, 2018 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 classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students for 10 summer weeks.

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

E.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.
2. $2000 - Travel expenses for the masters student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given eight invited talks at conferences, universities, and JLab reviews and fourteen Collaboration Chair reports at six CLAS Collaboration meetings. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

   Total = $5,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given eight 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.

G.1 - $1,195 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab).

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI, 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, 2019 - May 31, 2020)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $18,000 whichever is smallest.

B.2 One masters student for seven months (June-December, 2019) followed by a second student (February-May, 2020) both at an annual stipend of $29,500 prorated for their time in the program. In the Surrey program the students' research year runs February to December. The dates for this contract are June 1, 2019 - May 31, 2020 so the programs are out of phase. We include the support for the full research year in the 2019-2020 grant period and it is split between the end of the first student's time at JLab (2019) and the beginning of the second (2020). There are no tuition costs for this student. This student is classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students for 10 summer weeks.

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

E.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.
2. $2000 - Travel expenses for the masters student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given eight invited talks at conferences, universities, and JLab reviews and fourteen Collaboration Chair reports at six CLAS Collaboration meetings. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

   Total = $5,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given eight 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.

G.1 - $1,860 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab).

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI, 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, 2020 - May 31, 2021)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $18,000 whichever is smallest.

B.2 One masters student completing their research year (seven months in 2017). The stipend for the student in 2020 is prorated for the time in the program. In the Surrey program the students' research year runs February to December. There are no tuition costs for this student. This student is classsified as professional personnel because they are not Richmond students.

B.4 Two undergraduate students for 10 summer weeks.

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

E.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.
2. $2000 - Travel expenses for the masters student to attend one conference to present their findings.
3. $2000 - Domestic travel expenses for invited talks for the PI. Over the last three years Gilfoyle has given eight invited talks at conferences, universities, and JLab reviews and fourteen Collaboration Chair reports at six CLAS Collaboration meetings. There are some University funds for this travel, but they are limited and the PI has made heavy use of them in the last three years.

Total = $5,000

E.1 Foreign travel:

1. $2000 - Additional travel expenses for one foreign invited talk. Over the last three years Gilfoyle has given eight 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.

G.1 - $1,623 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab).

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI, undergraduates and the Surrey masters student (who will spend more than 50% of their time away from the University of Richmond campus).