Medium Energy Nuclear Physics Research at the University of Richmond

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Abstract

The nuclear physics program at the University of Richmond is focused on the structure of nucleons and the transition from the hadronic picture of matter to a quark-gluon description. We 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. We will extend this work to higher energy as part of the JLab 12-GeV Upgrade and experiment E12-07-104 (spokesperson: Gilfoyle) to measure the neutron magnetic form factor.

1 Project Introduction

This is a renewal application to support the University of Richmond electromagnetic nuclear physics research program at the Thomas Jefferson National Accelerator Facility (JLab). Dr. G.P. Gilfoyle is the principle investigator (PI) and the physics projects are listed in Table 1.

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
The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Electron-Neutron to Electron-Proton Scattering in Deuterium	E94-017
Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)	CLAS-Approved Analysis[1]
CLAS12 Software Architecture	
Bose-Einstein Correlations at an Electron-Ion Collider	INT-10-3
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 (2008). The analysis of two of the three data sets to extract the neutron magnetic form factor G_M^n is complete. The data were collected with the CLAS6 detector in Hall B at JLab during the E5 run period and the results were published in Physical Review Letters [1]. The PI is spokesperson and contact person for a PAC32-approved experiment to measure G_M^n using similar methods at higher Q^2 after the 12 GeV Upgrade at JLab is complete (experiment E12-07-104). That experiment will be performed in Hall B using the CLAS12 detector now under construction. It was reviewed again by PAC35

[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.

in January, 2010 and received a scientific rating of A^- and was allocated thirty days of beamtime. A large portion of our work has been focused on preparations for E12-07-104 (see Section 2.1.1). The CLAS12 electromagnetic calorimeter (EC) is an essential component of the G_M^n measurement (to detect neutrons) and Gilfoyle added the EC to the CLAS12, physics-based simulation (*gemc*) [2]. The detection of neutrons in the CLAS12 forward, time-of-flight (FTOF) was simulated with *gemc* and found to be consistent with past measurements of the neutron detection efficiency in CLAS6 [3]. A simulation of the target has been installed in *gemc* [4]. Finally, Gilfoyle joined the E12-09-019 collaboration to make a complementary measurement of G_M^n in Hall A.

With our collaborators we have developed a new, programming infrastructure for CLAS12 using service-oriented architecture (SOA) for event reconstruction (see Section 2.1.2)[5]. We relied heavily on the new Richmond Physics computing cluster acquired via an NSF Major Research Instrumentation grant in 2010 (see Section 2.1.6). Gilfoyle has taken on a leadership role in planning for CLAS12 software (see Section 2.1.5). He organized a workshop on CLAS12 software held at the Richmond in 2010, represented the CLAS Collaboration at an internal, JLab review of computing in 2011, and is now part of the team writing a software planning document.

The analysis of the out-of-plane structure functions of the deuteron in the $^2\mathrm{H}(e, e'p)n$ reaction is nearing completion. A draft of the technical report has been written and is being reviewed by our research team before submission to the Collaboration for internal review (see Section 2.1.3).

Gilfoyle was part of the group developing the scientific case for a next-generation accelerator, the Electron-Ion Collider, to study how hadrons emerge from the underlying forces of Quantum Chromodynamics (QCD). This work was part of the program at the Institute for Nuclear Theory at the University of Washington (see Section 2.1.4) [6]. In other contributions, Gilfoyle completed his tenure as chair of the Nuclear Physics Working Group and member of the CLAS Coordinating Committee. Over the last three years he gave five invited talks on JLab-related physics, fourteen reviews and updates at Collaboration meetings, eight contributed presentations, published three conference proceedings, and presented nine public lectures on physics, education, and science policy.

We now summarize our Plan of Work. One of the main foci of our work will be preparations for the future G_M^n measurement, in particular on simulation, analysis, and reconstruction (see Section 2.2.1). We will continue work on the design of the dual-cell target. A second major focus will be analyzing the remaining E5 data set to extract G_M^n (see Section 2.2.2). These data could have considerable impact on the experimental situation in the range $Q^2 < 1$ (GeV/c)^2. We will continue our work on software planning that begin in 2011 (see Section 2.2.3).

We will continue the analysis of the fifth structure function in quasielastic kinematics for the reaction $^2\mathrm{H}(e, e'p)n$ (Section 2.2.4) to establish a baseline for the hadronic model at low Q^2. As mentioned above, a draft of the technical report is being reviewed within our research team.

We also ask for funds to support masters students in a cooperative program between the University of Richmond and the University of Surry in the UK (see Section 2.3). Undergraduates from Surry are selectively admitted to the masters program and are required to spend one year (Jan-Dec) doing research. These students' work would be 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 enhance our productivity and the learning experience for our Richmond undergraduates. The Surry 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 Surry students and many of these students have gone on to US graduate schools, enhancing the US workforce.

2 Project Description

2.1 Status of Current Projects

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 [7], it is Milestone HP4 in the DOE Performance Measures [8], and it forms a central part of the past and future physics programs at Jefferson Lab (JLab) [9, 10, 11]. We are part of a broad assault on the four elastic nucleon form factors (electric and magnetic ones each for the proton and neutron) at JLab that include six experiments approved for running in the first five years after the 12 GeV Upgrade at JLab [10, 11]. The Upgrade will double the beam energy and expand the physics reach of the Laboratory. Our role is two-fold. (1) Gilfoyle is the spokesperson and contact person for JLab experiment E12-07-104 to measure G_M^n, the neutron magnetic form factor in Hall B using the CLAS12 detector now being built. (2) We have also taken on the analysis of the existing data collected with the current detector in Hall B (CLAS6) to extract G_M^n.

To measure G_M^n we use the ratio R of quasielastic (QE) $e-n$ to $e-p$ scattering on a deuterium target (since there are no neutron targets). The ratio method is less sensitive to experimental effects like variations in luminosity, detector gain, *etc*, but it does require a precise knowledge of the proton and neutron detection efficiencies to to keep systematic uncertainties under control. In the CLAS6 measurement, a unique, co-linear, dual-cell target was successfully used that included liquid deuterium for the production measurements and liquid hydrogen for determining the detection efficiencies. The calibrations were done *in situ*; simultaneously with the production measurements so the calibration data were taken under the same conditions. Systematic uncertainties in the final, CLAS6 G_M^n measurement were kept under 3%. The same approach has been approved for the CLAS12 measurement (E12-07-104).

The proposal for the planned, CLAS12 measurement of G_M^n was approved by PAC32 in August, 2007. In January, 2010 (during the current funding period) we submitted an update requested by JLab PAC35. The PAC reviewed eight previously approved experiments in the category entitled 'Transverse Structure of Nucleons' to assign a scientific rating and allocate beam time. Gilfoyle presented the update at the PAC meeting. The experiment received an A$^-$ rating (only one experiment had a higher rating in this category) and was awarded 30 days of beam time during the first five years of running after the 12 GeV Upgrade is complete [10].

We now discuss our work during the last three years to prepare for the new CLAS12 in general and for the G_M^n measurement in particular. In our last renewal in 2008, we made a commitment to the 'design, prototyping, development, and testing of software for event simulation and reconstruction in CLAS12' and have focused much of our efforts in these areas. The importance of software development in preparation for the start of the 12 GeV era has grown. JLab Director Hugh Montgomery has stated publicly the goal of being able to analyze and calibrate data from turn-on and in an internal JLab review of the computing enterprise at the Laboratory in May, 2011, the review committee stated that 'it is the desire of the laboratory to have all computing systems and software ready, so that the time from beam on target to physics journal articles is as short as possible' [12, 13, 14]. We are committed to reaching that goal.

As mentioned above, measuring the detection efficiencies is an essential part of the CLAS6 and CLAS12 measurements of G_M^n. The neutrons will be measured independently in two of the CLAS12 subsystems, the forward time-of-flight (FTOF) scintillators and the electromagnetic calorimeter (EC). This double measurement provides a powerful, internal consistency check of our analysis and was used in the CLAS6 measurement [1]. We have simulated the QE electron-neutron scattering in CLAS12 with the physics-based, CLAS12 simulation package *gemc* [15]. Electrons were reconstructed with the CLAS12 reconstruction code *Socrat* [16] and we have modified that program to add the neutron reconstruction. We studied the neutron detection efficiency (NDE) of the CLAS12 FTOF system to establish a baseline for the future G_M^n measurement. We found an efficiency of 16% for the most forward-angle scintillator panels and a value of 8% for the larger-angle panels. A comparison of the simulated efficiency for two FTOF panels that are being reused from CLAS6 with the measured values is shown in Figure 1. The simulated neutron detection efficiency is shown (blue points) as a function of neutron momentum along with the NDE measured at $E = 4.2$ GeV in CLAS6 (black points) [1]. The dip in the efficiency at $p_n \approx 3$ GeV/c is due to a small gap between two of the FTOF panels. This gap will be covered in the final CLAS12 by a new FTOF panel (it is removed in this simulation). There is good agreement between the simulation and the measured NDE. This work is described in CLAS-NOTE 2011-015 [3].

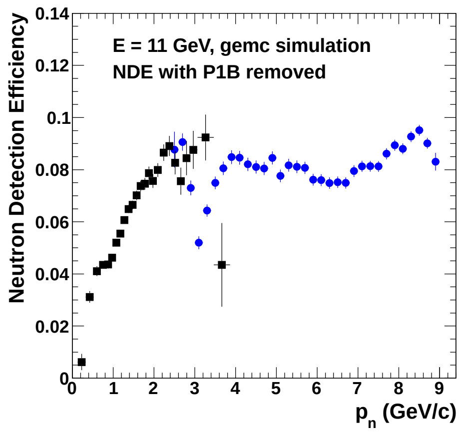


Figure 1: Comparison of simulated (blue) and measured (black) NDE.

The CLAS12 simulation package *gemc* is still under development. At the start of the current funding period, the EC (which will be used for neutron detection in E12-07-104) was not part of the code. We have added it to *gemc*. We streamlined the original geometry model to eliminate redundant parameters (the EC is being re-used from CLAS6) and implemented it in *gemc* using Geant4 [17]. Data banks are constructed to match the signals that will be measured and digitized to mimic the CLAS12 electronics. We have tested this new code. Straight tracks were directed at the edges of the EC to check the geometry. We used the simulated deposited energy deposited and the known incident electron energy to extract the EC sampling fraction (ratio of the energy deposited to incident energy), the EC energy resolution, and the transverse shower size. We found good agreement with the standard CLAS6 simulation GSIM [18]. This work is described in CLAS-NOTE 2011-019 [2].

We have also developed a simulation of the dual-cell target for E12-07-104 in *gemc*. It consists of two cells each 1.5 cm long with 2.0 cm separating the cells. Figure 2 shows the target in *gemc*. We have begun studying our ability to separate tracks from the two targets in the reconstruction. This work was an undergraduate project [4].

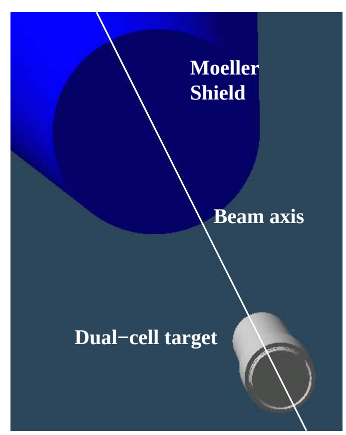


Figure 2: Co-linear, dual, hydrogen-deuterium target for *in situ* calibration.

We now discuss our work on existing CLAS6 data to extract G_M^n. We have completed data collection and the analysis for a measurement of G_M^n in the range $Q^2 = 1.0-4.8$ GeV^2 using two out of the three sets of running conditions from the CLAS6 E5 running period [1, 19, 20]. During the previous funding period we took the lead in completing the internal, CLAS Collaboration review of the analysis and writing the paper. The first paper describing these results was published during the current funding period (May, 2009) in Physical Review Letters [1]. The third data set reaches covers the range $\mathrm{Q}^2 \approx 0.3 - 1.0$ GeV^2 and overlaps with measurements from other experiments. This region has been the focus of intense interest over the last few years [9, 21, 22]. We are now analyzing those data. We have extracted the neutron and proton detection efficiencies, calculated the Fermi correction, and matched the $e-n$ and $e-p$ solid angles to determine the ratio R of quasielastic $e-n$ to $e-p$ scattering.

In the last two years we joined a collaboration in Hall A to make a complementary measurement of G_M^n at JLab [23]. In this experiment, E12-09-019, we will use the same ratio method on deuterium as in the CLAS12 experiment. The $e-n$ and $e-p$ events will be detected with the proposed Super-BigBite spectrometer in Hall A [24]. The neutron detection efficiency will be measured separately with the $p(\gamma, \pi^+ n)$ reaction using the endpoint method to identify two-body final states. We worked with the spokesperson (B.Wojtsekhowski) on the update for PAC35 (the same review mentioned above for the CLAS12 G_M^n experiment). The Hall A experiment has lower statistical uncertainty than CLAS12 at the highest Q^2 points, but the large solid angle of CLAS12 allows us to veto three-particle final states that contaminate the quasielastic peak. The PAC35 report states the two measurements will 'allow a better control for the systematic error' [10]. PAC35 gave a scientific rating of B+ to the Hall A experiment and allocated 25 days of beamtime.

2.1.2 CLAS12 Software Architecture

Modern high energy and nuclear physics experiments require more computing power to keep up with increasing experimental data volumes while at the same time functioning within large, diverse collaborations. The traditional physics computing model is based on self-contained, monolithic software applications running in batch mode. This approach has been found to be difficult to maintain, difficult for new users to use, and less adaptable to modern multi-core, multi-threaded, distributed computing environments. The CLAS12 Software Group is developing a service-oriented architecture (SOA) to solve this problem. A service here is a software component (*i.e.* a piece of code or a data structure) that is reusable and where the access is provided using a well-defined interface. The use of the interface has to be consistent with constraints and policies specified by the service description. The services are loosely couple meaning each each service/component has little or no knowledge of other services, *i.e.* the electron tracking code consists of a chain of services (segment finding, linking segments together, *etc.*) that are independent of one another [5].

The CLARA (CLAS12 Reconstruction and Analysis framework) SOA is under development by Gyurjyan *et al.* for CLAS12. The package is running with about twenty services deployed including cluster finding, track segment finder, *etc.* The Richmond role has been two-fold. First, the Richmond Physics Cluster (see Section 2.1.6) has been the tool of choice for our collaborators to write code. Second, we are the first ones to attempt to link a C++ service (for neutron reconstruction) with the CLARA tracking service written in Java. A Richmond undergraduate, computer science major is working on this project.

2.1.3 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 to establish a baseline for the hadronic model of nuclei to meet. The data were measured with the CLAS detector at JLab and consist of two data sets both at a beam energy of 2.6 GeV, but with opposite torus magnet polarities so they cover different Q^2 ranges. These are the same data sets studied in the G_M^n analysis (see Section 2.1.1). This baseline is necessary to map the transition from hadronic to quark-gluon degrees of freedom at higher Q^2 (see NSAC Long-Range Plan [7]). We are extracting the fifth structure function which is the imaginary part of the LT interference and has not been studied extensively in the past. The cross section for the ${}^2\mathrm{H}(\vec{e}, e'p)n$ reaction with a polarized beam and unpolarized target can be written as

$$\frac{d\sigma^5}{d\nu d\Omega_e d\Omega_{pq}} = \sigma_L + \sigma_T + \sigma_{TT}\cos\phi_{pq} + \sigma_{LT}\cos 2\phi_{pq} + h\sigma'_{LT}\sin\phi_{pq} \tag{1}$$

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

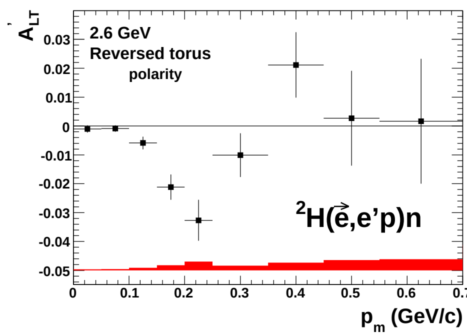


Figure 3: Preliminary results for helicity asymmetry A'_{LT} for $^2\mathrm{H}(\vec{e}, e'p)n$.

During the current grant period we have refined our quasielastic event selection, tested the analysis algorithms in simulation with a known asymmetry and validated our code, and completed the extraction of systematic uncertainties for both data sets. Some of our preliminary results for A'_{LT} as a function of the missing momentum p_m are shown in Figure 3. The missing momentum is $\vec{p}_m = \vec{q} - \vec{p}_p$ where $\vec{p}_p$ is the measured proton 3-momentum. The red bar graph shows the systematic uncertainty which is small across the full range of p_m. A draft of the CLAS Analysis Note has been prepared and we are currently refining it in our analysis group.

2.1.4 Bose-Einstein Correlations at an Electron-Ion Collider

QCD directs the formation of hadrons from quarks and gluons in hard scattering, but there is no full, QCD-based theory to explain hadronization and fragmentation. The Electron-Ion Collider (EIC) has been proposed as the next-generation facility for nuclear physics to probe these questions and others [6]. In 2010, we were invited to explore the measurement of correlations between bosons (*e.g.* $\pi^+\pi^+$) to study the space-time extent of the source of the particles and/or learn about the dynamics of their formation. These Bose-Einstein Correlations (BEC) occur when particles are formed near one another so their wave functions overlap and interfere - producing correlations in the intensity and momentum dependence of the final particles. For example, the difference in the longitudinal and transverse (relative to the momentum transfer) size of the emitting source in eA collisions may reveal the properties of the QCD 'string' in nuclear matter [25, 26, 27, 28, 29].

We have simulated $\pi^+\pi^+$ BECs from eA collisions at EIC kinematics using the code PYTHIA [30]. We see significant correlations at $Q_{12} \approx 0$ where Q_{12} is the magnitude of the 4-momentum difference between the two pions. A significant correlation here implies that a large fraction of the pions are correlated in the source. We have shown that we can expect to extract sources sizes with a resolution of about $0.1 - 0.2\ fm$. Bose-Einstein Correlations are a promising tool for studying the properties of nuclear matter at the EIC. This work is published in Ref. [31].

2.1.5 CLAS12 Software Planning and Collaboration Service

The CLAS12 detector will have prodigious computing requirements. With the high luminosity ($10^{35} cm^{-2}s^{-1}$) we expect to collect about 10^{11} events each year requiring more than a PByte/year of storage just for the raw data. See Section 2.2.3 and Table 2 for more details. At Richmond we have taken on software tasks needed to make CLAS12 a success (see Sections 2.1.1-2.1.2) and we have also taken a leadership role in planning and preparing for the 12 GeV era. In May, 2010 the University of Richmond hosted the CLAS12 Software Workshop. Gilfoyle was chair of the organizing committee. The first day was focused on talks from outside experts from Brookhaven National Lab and FermiLab, JLab staff, and members of the CLAS12 software group [32]. The second day was used for tutorials to teach the participants how to use the new software tools. About

50 people attended. The workshop was funded, in part, by a grant from the JSA/SURA Initiatives Fund. In May, 2011 Gilfoyle presented the status of the CLAS12 software at an internal JLab review 'Information Technology for the 12 GeV Era' [14]. He is also a co-author of the CLAS12 Software Planning Statement now in preparation which lays out a conceptual design of the software and makes recommendations on ways to insure its accuracy, agility, and efficiency. During the current funding period Gilfoyle completed his term as chair of the Nuclear Physics Working Group.

2.1.6 University of Richmond Physics Computing Cluster

Central to the productivity of our research group at Richmond is the acquisition of a new computing cluster in 2010. With a faculty colleague at Richmond we submitted a proposal to the NSF's Major Research Instrumentation program and received a $162,000 grant to replace our aging cluster. The new system consists of twenty, 2.66 GHz, dual-6-core, remote nodes each with 24 GByte of RAM and 1 TByte of storage. The head node is a 2.66 GHz, dual-6-core machine also with 24 GByte of RAM. A file server provides 5 TByte of space. The system has been used for nearly all projects here and has been the main development tool for CLARA (see Section 2.1.2) [5, 33].

2.1.7 CLAS6 Online Monitoring Tools

We are responsible for maintaining a CLAS6 online monitoring tool called online RECSIS [34, 35]. The incoming data are monitored to detect problems with a modified version of the CLAS analysis package. The datastream is read and a full, event reconstruction is done on a subset of the data. Histograms are accumulated and timelines of the results are generated and posted to the web. The code has been operating reliably for years, but requires occasional maintenance.

2.1.8 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and the quest to understand confinement is an essential goal of nuclear physics. Confinement can be investigated by striking a quark with a photon and stretching out the color string tying it to its neighbors. Gilfoyle is a co-spokesperson on a 12-GeV experiment E12-06-117 *Quark Propagation and Hadron Formation* that lays out a program to determine the mechanisms of confinement in forming systems. We will be responsible for the analysis of the π^0, η, and η' exit channels. The experiment was reviewed by PAC36 and received a scientific rating of A^- and was allocated 60 days of beamtime.

2.1.9 Summary

Since our last renewal in 2008, the G_M^n paper was published in Physical Review Letters [1] and the G_M^n (E12-07-104, Section 2.1.1) and hadron attenuation (E12-06-117, Section 2.1.8) experiments were reviewed and received high scientific ratings. We completed the addition of the electromagnetic calorimeter to the CLAS12, physics-based simulation and tested that component along with the simulation of the forward time-of-flight system. The software infrastructure for CLAS12 has advanced considerably with support from the Richmond computing cluster and with contributions from the Richmond students. Our analysis of the fifth structure in $^2\mathrm{H}(\vec{e}, e'p)n$ is nearly complete and we contributed to the scientific case for the EIC. We also worked on software planning for CLAS12.

2.2 Plan of Work

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

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 4-6 GeV, a 100% duty cycle, and a maximum current of 200 μA. Our research is done in Hall B with the CEBAF Large Acceptance Spectrometer (CLAS6). CLAS6 is a large (45-ton), toroidal, multi-gap magnetic spectrometer with nearly full solid angle coverage (see Figure 4). A toroidal magnetic field is generated by six iron-free superconducting coils. The

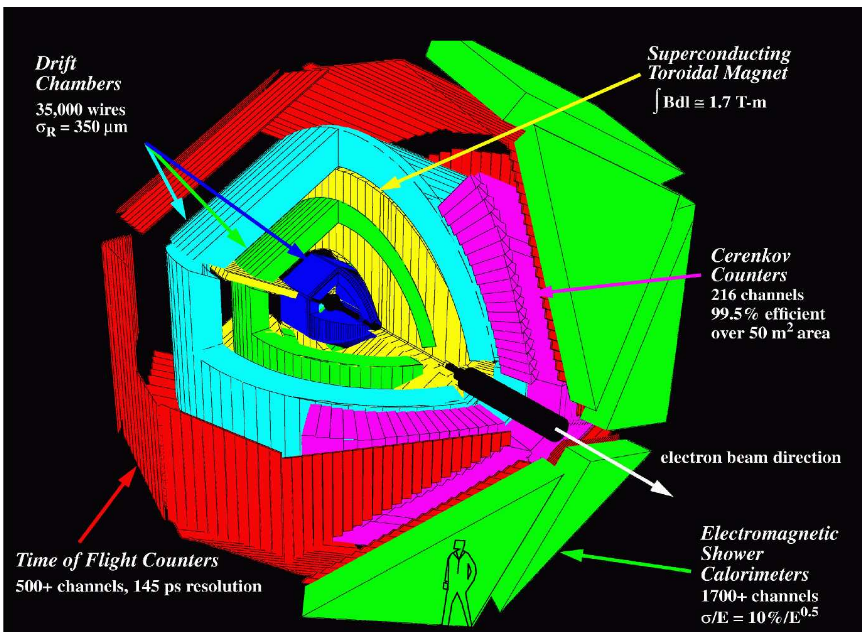


Figure 4: The CLAS6 detector.

particle detection system consists of drift chambers [36] to measure charged particle trajectories, Cerenkov detectors [37] to identify electrons, scintillators [38] for time-of-flight measurements, and electromagnetic calorimeters [39]. The six segments are instrumented individually to form six independent spectrometers. The Richmond group has been part of the CLAS Collaboration that built and now operates the detector since its inception.

Jefferson Lab is now in the midst of the 12 GeV Upgrade project to double the beam energy, enhance the capabilities of the existing experiment halls, and construct a new detector in Hall D. The left-hand panel of Fig. 5 compares the kinematic reach before and after the Upgrade in terms of Q^2 and the $M\nu$, the product of the nucleon mass and the energy transfer from the scattered electron. There is a dramatic increase in the kinematic reach of CEBAF which opens up new physics opportunities. Completing the Upgrade is the highest priority in the current NSAC Long-Range Plan [7].

A largely new detector will be built in Hall B called CLAS12 to take advantage of these new physics opportunities. CLAS12 (right-hand panel of Fig. 5) will be able to operate at ten times

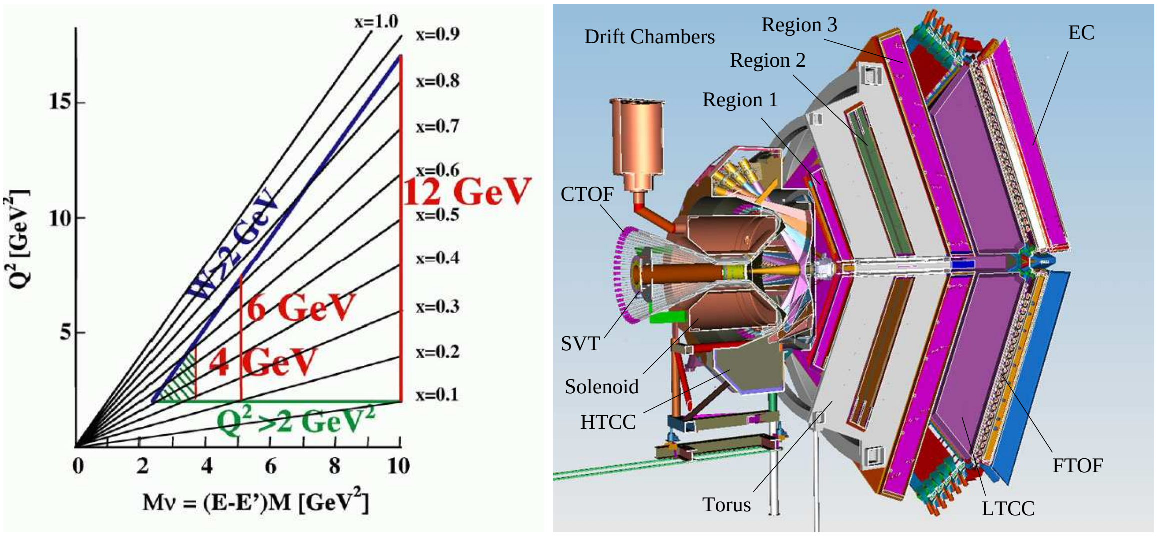


Figure 5: Comparison of the kinematic reach of JLab before and after the 12 GeV Upgrade (left-hand panel) and the CLAS12 detector in Hall B (right-hand panel).

higher luminosity (10^{35}cm^{-2}s^{-1}) than CLAS6 and will consist of both forward and central detectors. The Forward Detector will retain the original six-sector configuration of CLAS6 (the electromagnetic calorimeters and some time-of-flight panels will be reused) with a new torus magnet and other improvements (*e.g.* silicon vertex tracker, preshower calorimeter, high-threshold Cerenkov counter, *etc.*) to measure particle production in the range $\theta = 5^\circ - 40^\circ$. The Central Detector is based on a solenoid magnet and will be optimized for large-angle particle production ($\theta = 35^\circ - 125^\circ$). We are committed to development projects for the Upgrade and are responsible for design, prototyping, development, and testing of software for event simulation and reconstruction.

2.2.1 Magnetic Form Factor of the Neutron - Future Measurement

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 unconquered territory of the nonperturbative region [7]. 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. One of the central questions raised in the NSAC Long-Range Plan is 'What is the internal landscape of the nucleons?' [7]. The neutron magnetic form factor G_M^n is one of the fundamental quantities of nuclear physics and its evolution with Q^2 characterizes the distributions of charge and magnetization within the neutron. It is central to our understanding of nucleon structure. Our role in this part of the project is twofold. First, Gilfoyle is the spokesperson and contact person for JLab Experiment E12-07-104 which will measure G_M^n with the CLAS12 detector in Hall B and was approved by JLab PAC32. We propose to develop software for simulating the performance of the CLAS12 detector and analyzing the results. The JLab management and the CLAS Collaboration now 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 [12, 13, 14]. The projects we describe below are aimed at both preparing for E12-07-104 and fulfilling this Collaboration and Laboratory goal. Second, working with the technical and scientific staff at JLab we will begin development of the dual-cell liquid-hydrogen-liquid-deuterium target for

E12-07-104. Turn-on is expected in 2015 so target preparations should begin in the next funding period.

We now discuss our current understanding of G_M^n and nucleon structure. We expect to obtain a new, unprecedented tomographic view of the interior of the nucleons through the measurement of generalized parton distributions (GPDs). The elastic form factors are a limiting case related to the zeroth moment of the GPDs and provide a vital constraint on GPD models [40]. Lattice QCD calculations are now becoming feasible in the few-GeV^2 range, and over the next decade these calculations will become increasingly precise [41]. The elastic form factors for both the proton and neutron are an important test case of the accuracy of the lattice calculations. With all of them, one can determine the isovector combinations of the form factors [42] which are easier to calculate on the lattice because of the lack of disconnected contributions [43]. We are part of a wide effort to measure the four elastic nucleon form factors at Jefferson Lab; six experiments have been approved for running in the first five years [10].

The discovery potential 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. The anticipated results for E12-07-107 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 three curves illustrate three different attempts to describe the data: a constituent quark model using the light-front formalism (long-dashed curve from Miller [51]), a GPD-based calculation (dotted curve from Guidal *at al.* [52]), and a calculation based on the Dyson-Schwinger equation (dashed curve from Cloet *et al.* [53]). All three calculations are different for Q$^2 > 7$ (GeV/c)^2 above the range of nearly all the existing data. The planned G_M^n measurement will have the precision to distinguish among them.

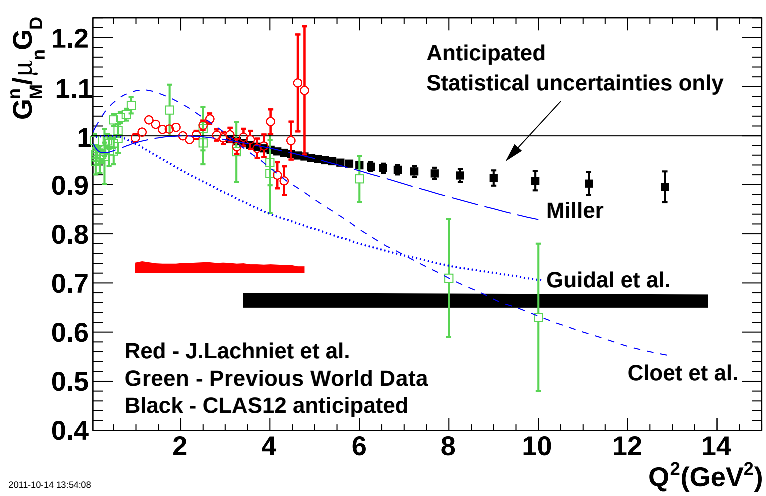


Figure 6: Results for $G_M^n/(\mu_n G_D)$ from CLAS6 (red), previous data (green) [44, 45, 46, 47, 48, 49, 50], theoretical calculations, and expected data from CLAS12 (black) are shown.

Our method to measure G_M^n relies on the ratio R of $e - n$ to $e - p$ 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 measurement [1]. The differential cross section for elastic electron-nucleon scattering can then be calculated in the laboratory frame as [54]

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

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, $\tau = Q^2/4M^2$ where M is the nucleon mass, and $\epsilon = (1 + 2(1 + \tau)\tan^2(\theta/2))^{-1}$ where θ is the electron scattering angle. To obtain G_M^n we use the ratio R defined as

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

where E is the beam energy and $a(E,Q^2)$ corrects for nuclear effects.To select quasielastic 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]. 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, 19, 20]. The extraction of G_M^n depends on our knowledge of the other three nucleon form factors, but the proton form factors are precisely known and the neutron's electric form factor G_E^n is typically small so their impact on the systematic uncertainty is limited. This technique does require precise knowledge of the neutron detection efficiency and careful matching of the neutron and proton acceptances. To measure the neutron detection efficiency a unique dual-cell, co-linear, liquid-hydrogen-liquid-deuterium target is used. The $ep \to e'\pi^+n$ reaction is a source of tagged neutrons which are detected in two, overlapping measurements with both the electromagnetic calorimeter and the forward time-of-flight system; providing a powerful consistency check on the measurements. To measure the proton detection efficiency we use elastic ep scattering on the hydrogen target to make tagged protons. Acceptance matching is done event-by-event by detecting the electron, assuming QE scattering, and calculating the track for both proton and neutron. If both particles are expected to strike the active area of the detector, we continue with the analysis, otherwise the event is rejected. Corrections for Fermi motion of the nucleons in the deuteron are calculated in simulation. The methods described here were successful in our previous analysis of the CLAS6 E5 data [1]. For E12-07-104 we found that an additional requirement was needed to keep the inelastic background under control. The width in W^2, the square of the residual mass left behind by the scattered electron, increases with increasing Q^2, contaminating the QE peak. The effect is shown in simulation in Fig 7. The left-hand panel shows, the spectrum from a simulation of $e-n$ events from deuterium with $\theta_{pq} < 1.5°$. The

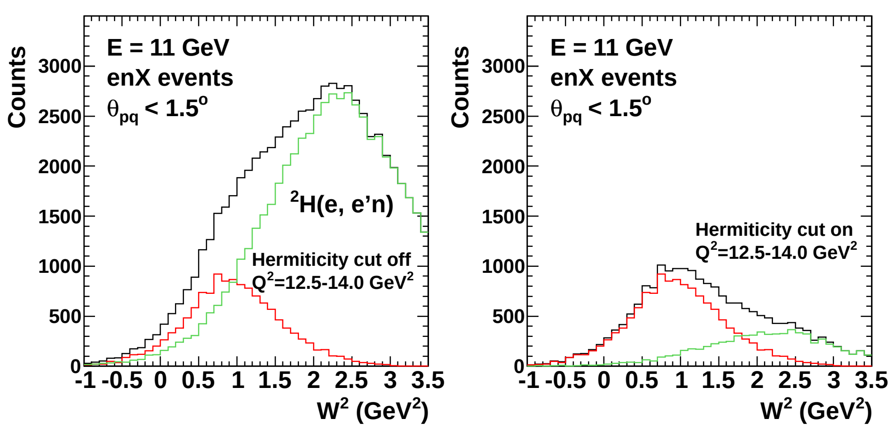


Figure 7: The effect of requiring no additional particles in the final state (hermiticity cut) is shown in the highest Q^2 bin where the inelastic contamination will be greatest.

background (green histogram) overwhelms the QE peak (red histogram). The black histogram is the sum of the other two. In the right-hand panel we reject any events from the sample in the left-hand panel that contain a third particle in the final state. It shows a dramatic drop in the inelastic background so we will have the inelastic backgrounds under control.

To prepare for E12-07-104 we propose developing software for CLAS12. In particular we will develop simulation, analysis, and tracking code for the CLAS12 electromagnetic calorimeter (EC). At this point in time a physics-based simulation of CLAS12 called *gemc* exists [15] that includes the EC (we added the EC part, see Section 2.1.1 and Ref. [2]). An EC analysis code has been developed by our collaborators in Valparaiso, Chile, starting with the CLAS6 code and that code determines the position and light-output of different particle showers. However, there is room for further improvement. The first goal of this part of our program is to study the EC performance in the 11-GeV environment focusing, in particular, on neutron detection. This study has not been done with *gemc* as we have done with CLAS12 FTOF (see Section 2.1.1 and Ref. [3]). We will also study neutron detection efficiency in the EC at low neutron momentum to compare with the measured and calculated results from CLAS6 [1, 18, 55, 56]. Additional lines of research include optimizing the performance of the analysis code for parallel processing, simulating the flash ADC performance, adding the FTOF and EC analysis to the tracking, *etc.* All of these topics need attention so that the CLAS Collaboration can be ready to analyze data at turn-on. We are coordinating our efforts with the CLAS12 Software Group to work on the highest priority software needs as that day approaches.

We also propose beginning target development during the next funding period. In the current schedule physics running will begin in 2015 and it typically takes about one year to develop a target like the one discussed here. It is prudent to begin those preparations during the next funding period which runs to May, 2015 to be ready for possible early physics running of E12-07-104. The design is modeled after the E5 target used for the CLAS6 G_M^n measurement [57]. As mentioned above and shown in Figures 2 and 8 we will use a dual-cell target.

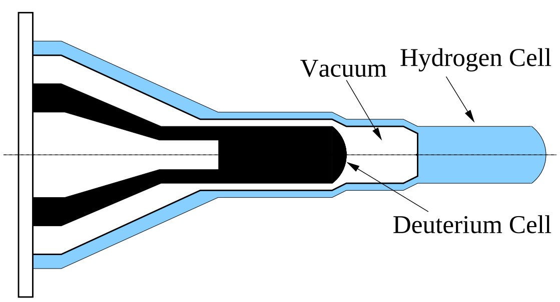


Figure 8: The CLAS12 G_M^n target.

An upstream (left) cell will hold liquid deuterium for production running and the downstream cell will hold liquid hydrogen for calibrations (neutron and proton detection efficiencies). The cooling lines and support structures will be attached at the upstream end of the target to minimize the material in the path of scattered particles. In the current design each cell is 1.5 cm long with a 2 cm gap in between the cells. The three-dimensional shape of the target can be obtained by rotating the target in Figure 8 about the beam axis (dashed line) so the supply lines are actually conical shells. We have incorporated a simulation of the material of the target in *gemc* (the CLAS12 simulation) using Geant4 and have begun using it to study the properties of events scattered from the two cells (see Section 2.1.1). Some of the issues to investigate include the optimum distance between the cells so we can separate events from the two targets, acceptance effects, calibration procedures, cell sizes, materials used and their thicknesses, angle limits on scattered particles, luminosity limitations, *etc.* Reference [57] has a full discussion of many of this issues for the CLAS6 E5 target. Depending on the schedule of physics running we will also begin the design of the target during the next funding period. We will be working with D. Kashy, S. Christo and the engineering staff in Hall B. To summarize this part of our proposal to measure the neutron magnetic form factor during the next three years, there are two pieces. (1) We are leading the preparations for JLab Experiment E12-07-104 and will develop the software resources necessary to analyze data from CLAS12 at startup in 2015. (2) We will begin preparations to build the dual-cell target for E12-07-104.

2.2.2 Magnetic Form Factor of the Neutron - Current Analysis

We now describe our plan to extract G_M^n from existing data at low Q^2. The current status of our understanding is shown in Figure 6. The red points represent the recent work by Lachniet, *et al.* and our E5 group [1, 19, 20]. The green points are from selected experiments including precise measurements of the reduced form factor by Anderson, *et al.* (at JLab), Anklin, *et al* [48] and Kubon, *et al.* [46] that use the ratio method similar in many respects (but not all) to the method we use (see Section 2.2.1). We focus here on $Q^2 < 1.0$ GeV^2. Our measurement in Fig. 6 at $Q^2 \approx 1.0$ (GeV/c)^2 is about 6-7% below the one by Kubon *et al.*. The data from Anklin *et al.* range from 2-5% above the dipole and are a few percent above the Anderson *et al.* results where they overlap. We have preliminary results in this Q^2 range that agree with Anderson *et al.* and are about 6-7% below the results of Anklin *at al.* and Kubon *et al.*. We also have data from the E5 running period that is still being analyzed that overlaps with the other measurements in this Q^2 region and extends down to $Q^2 \approx 0.3$ (GeV/c)^2.

We propose to complete the extraction of G_M^n from the E5 data. The E5 run consisted of three sets of running conditions. Two data sets were taken at beam energies of 2.6 GeV and 4.2 GeV with normal torus polarity (electrons inbending) and a third was taken at 2.6 GeV with reversed torus polarity to reach lower Q^2. We have taken on the analysis of the 2.6-GeV, reversed-torus-polarity data set from the JLab E5 running period. These data cover the range $Q^2 = 0.3 - 1.5$ GeV^2 and overlap with our 2.6-GeV, normal-torus-polarity data set and with the results from other groups. We expect statistical and systematic uncertainties of about 3% each and the E5 data set has abundant overlaps and consistency checks to insure the quality of the results, *e.g.* we have two, independent measurements of the neutron production in the CLAS6 electromagnetic calorimeter and the forward TOF system. This is an excellent opportunity to improve our understanding of nucleon structure with data we already have in hand.

2.2.3 CLAS12 Software Development and Planning

We are part of the team developing software for CLAS12 in preparation for the start of experimental running in 2015. The goal is to be ready to analyze data when beam arrives [12, 13]. The challenge in achieving this goal can be seen in Table 2. The computing requirements for CLAS12 are large

	Cores	Disk (TByte)	Tape (TByte/yr)
DAQ	-	-	1100
Calibration	127	-	-
Simulation	828	65	327
Reconstruction	393	370	3700
Analysis	463	370	370
Sum	1811	805	5497

Table 2: Summary of computing requirements for CLAS12.

and for the Collaboration to successfully analyze data at startup requires accurate, adaptable, and efficient code. Our role in this project is threefold. (1) We are developing software to simulate and analyze CLAS12 data (see Section 2.2.1), (2) we are building the software infrastructure for CLAS12, and (3) Gilfoyle is part of the CLAS12 software planning team.

Much of our work for developing CLAS12 software is also part of our preparations for the G_M^n experiment E12-07-104. When possible we try to combine the goals of software development and preparing for the experiment. Our plan of work for this software piece over the next three years is described in Section 2.2.1. We are also contributing to developing the CLAS12 software infrastructure. The reconstruction software will be based on CLARA, a service-oriented architecture (SOA). Services are distinct programing functions that have no knowledge of other services or share data with them and communicate only through a well-defined interface [5]. In other words, services provide a technological solution to programming modularity. The code is easier to manage and more adaptable to changing requirements. Much of the work over the last 18 months to develops CLARA has been done by V. Gyurjyan at JLab and his collaborators using Spiderwulf, the Richmond physics cluster that was obtained with an NSF MRI grant in 2010 (see Section 2.5 and Ref. [58]). This cluster has become the major development platform for CLARA. We provided local support with administration and code building. One of my undergraduate students was the first to attempt to develop a C++ service to add neutron reconstruction to the existing service-oriented reconstruction code (see Section 2.1.2). We will continue this work in the next funding period.

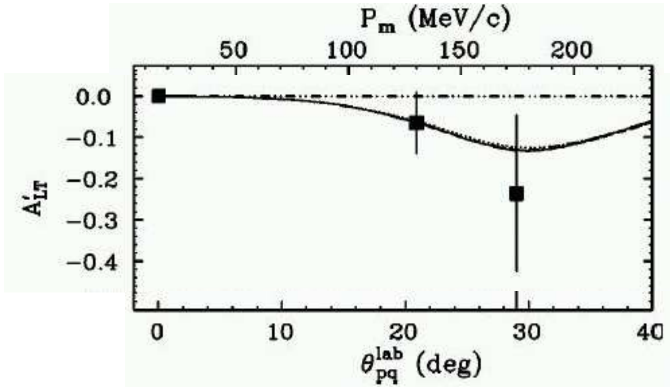
Software planning is the final part of our planned work for the next funding period. Gilfoyle has become one of the leaders of the CLAS12 Software group. He represented the Collaboration at the internal review mentioned above [13, 14] and is now working with other members of the team (D. Weygand (staff scientist and head of the CLAS Software Group), V. Gyurjyan (staff scientist and member of the DAQ group), and K. Hicks (Collaboration chair)) on a software planning document. He gave an interim report on software planning at the October, 2011 CLAS Collaboration meeting. During the next few months the draft of the planning document will be finished and then circulated among the CLAS Collaboration. Ultimately, this will be used as a vehicle for developing, planning, and monitoring software in a manner analogous to CLAS12 hardware and will help us reach the goal of being able to calibrate and analyze data when CLAS12 begins taking physics data in 2015.

2.2.4 Out-of-Plane Structure Functions of the Deuteron

We propose to measure the out-of-plane structure functions of the deuteron in the GeV region to test the hadronic model of nuclei. The hadronic model of nuclear physics has been successful at low Q^2, but it is not well-developed in the GeV region even though we expect it to be valid there. There are few data to challenge theory. The importance of relativistic corrections (RC), final-state interactions (FSI), meson-exchange currents (MEC), and isobar configurations(IC) is our focus here. Testing the hadronic model establishes a baseline necessary to answer one of the questions posed in the most recent NSAC Long-Range Plan: 'What governs the transition from quarks and gluons to pions and nucleons?' [7]. The importance of this issue was stressed in previous JLAB PAC studies [59].

We are investigating these out-of-plane structure functions of the deuteron using the reaction $^2\mathrm{H}(\vec{e}, e'p)n$ with CLAS. See Section 2.1.3 for the expression for the cross section and the kinematic observables. The structure functions are an essential meeting ground between theory and experiment and the unique, nearly-4π solid angle of CLAS coupled with the high-quality, polarized beams at JLab create an inviting opportunity to study σ'_{LT} which is the partial cross section related to the imaginary part of the longitudinal and transverse interference. These structure functions depend on ϕ_{pq} and have not been extensively investigated in the past. We are making a model-independent measurement of a little-studied part of the deuteron cross section that probes its wave function.

We access σ'_{LT} with the asymmetry A'_{LT} (see Section 2.1.3 and Eq. 1) and existing measurements of A'_{LT} are sparse. There are two measurements of $A_{LT'}$ in quasielastic kinematics at $Q^2 = 0.13$ GeV^2 [60] and 0.22 GeV^2 [61] and a single measurement at higher energy transfer ν at $Q^2 = 0.15$ GeV^2 [62]. Final state interactions (FSI) are dominant as shown in the left-hand panel of Fig. 9 [61] where the solid curve is a calculation with FSI turned on and the dashed-dotted line is the same calculation with FSI turned off. The challenge here is obtaining adequate statistics -



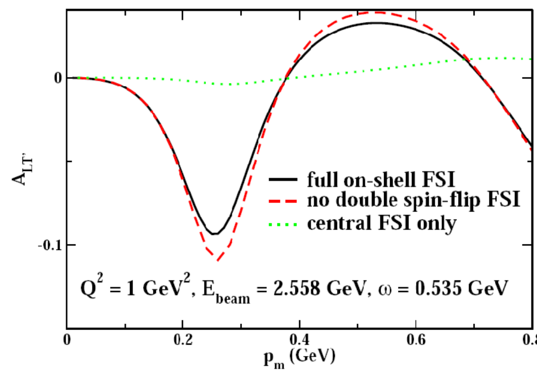


Figure 9: Measurements of A'_{LT} from Reference [61] at $Q^2 = 0.13$ (GeV/c)^2 are shown in the left-hand panel. The effect of spin-orbit FSI forces calculated in Reference [63] is shown in the right-hand panel.

compare Fig. 9 with our preliminary measurements in Fig. 3. We do much better.

We have been working with several theory groups (see Section 2.1.3). The fifth structure function is a sensitive probe of the spin-orbit part of the NN interaction. The plot in the right-hand panel of Fig 9 shows the calculated A'_{LT} from Jeschonnek and Van Orden (JVO) [63]. With the spin-flip scattering amplitude turned off (green, dotted curve), A'_{LT} goes nearly to zero. The red, dashed curve shows a dramatic effect when the spin-orbit part is turned on in the calculation. The double-spin components (solid curve) have little effect implying the spin-orbit part of the interaction is the primary contributor. As mentioned in Section 2.1.3 we have completed a draft of the CLAS Analysis Note which is the first step in the CLAS Collaboration procedure for publishing a paper.

2.2.5 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and its understanding is a central challenge in nuclear physics. We will investigate the nature of confinement by studying the hadronization process across a wide range of nuclei. This will enable us to extract the quark production times (*i.e.*, the lifetime of a bare, struck quark) and the hadron formation times (*i.e.* the time for a hadron to become fully dressed with its gluon field). These physics goals are focused on one of the central questions raised by the NSAC Long-Range Plan [7] ‘What governs the transition of quarks and gluons into pions and nuclei?’. Experiment E12-06-117 was approved by PAC30 and earned a scientific rating of A$^-$ from PAC36 in 2010 [64]. Gilfoyle is a co-spokesperson on the proposal and is responsible for analysis of the π^0, η, and η' channels along with K. Joo from the University of Connecticut. During the period of this grant we will continue work on the simulation of events in CLAS12. More details can be found in Sections 2.2.1-2.2.3.

2.2.6 CLAS Collaboration Service

During the period of this proposal we will continue to maintain the code for calculating radiative corrections for exclusive reactions on the deuteron [34, 35] and to maintain online RECSIS, one of the CLAS data-acquisition monitoring tools.

2.3 Graduate Student Support

We request in this proposal funding to support a masters-level student who will be engaged in the physics projects described here. The physics program in the next funding period is centered around two major themes: (1) preparation for the CLAS12 G_M^n measurement that has been approved for running in the first five years after the 12 GeV Upgrade and (2) the analysis of existing CLAS6 data on G_M^n. Our focus in (1) is on developing software for simulation and analysis that will have impact on the overall physics program for CLAS12. For (2) analysis of two of three data sets is complete so we will be able to make good progress on the analysis of the final data set. Our group at the University of Richmond consists of a single faculty member and 2-4 undergraduates working during the summers. The addition of a 12-month masters student would raise our productivity and enhance the intellectual environment in our research group and in the Physics Department at the University of Richmond.

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

We have thought carefully about how to structure this student's experience. (1) We would station the person in the Richmond office at Jefferson Lab. Gilfoyle routinely travels to JLab (see Section 2.5); he spent 63 days on site during the last year so there would be ample time for for collaboration. Gilfoyle is an active member of the CLAS12 Software group and the group provides a good working environment and community to work in. Three of the JLab staff scientists (Weygand, Gyurjyan, Ungaro) in the group are committed to supporting this student. (2) The student would spend some time (2-4 days per month) in Richmond typically on the Physics Department's seminar days. This would broaden the students' perspective by working in a university setting, interacting with Richmond undergraduates, and collaborating with the PI. In this proposal we ask for funding for this travel. (3) The program proposed here covers a significant range of topics from analysis of CLAS6 data to developing new tools for the CLAS12. We will work closely with the our collaborators at JLab and at Surry to match the students' skills and interest to the needs of the program. This is an exciting time at JLab and the program outlined here would embed the student in that community, provide abundant opportunities for working with the PI, and also give the student a taste of a university environment.

It is worth mentioning that this collaboration with Surry 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 Surry students and many of the students have gone on to US graduate schools, enhancing the US workforce. We also point out that stationing the masters student at JLab dramatically cuts the overhead rate.

2.4 Undergraduate Research at the University of Richmond

Undergraduates are part of all stages of this physics program and the funds requested will enable us to provide an intense summer research experience for these young people. Since 1987 Gilfoyle has mentored 2-3 undergraduates doing research almost every summer with about two-thirds going on to graduate school in science and engineering at places like Chapel Hill, UC Santa Barbara, Virginia, Princeton, and Stanford. Five have received doctorates. Three from our lab are currently staff scientists at NASA-Goddard, NASA-Huntsville, and the Jet Propulsion Laboratory, one is a faculty member at Stanford, and one is a researcher at Cornell in biological physics. Among students who recently worked in our laboratory one (Mark Moog) is now in graduate school in physics at Chapel Hill, another (Matt Jordan) is in graduate school in electrical engineering at Georgia Tech, and a third (Calina Copos) is a graduate student in applied mathematics at UC, Irvine. Our students use modern computational techniques for simulation and to 'mine' large data sets for information using our supercomputing cluster. They take shifts at JLab, attend collaboration meetings, present their work at local, national, and international conferences [4, 33, 65, 66, 67, 68], and are co-authors on technical reports [2, 3]. In the last three summers five students worked in my laboratory including one woman and a high school student who is now a physics major at Richmond. They were funded by a mixture of DOE grant and University funds.

2.5 Institutional Support and Resources

The nuclear physics group at the University of Richmond is supported by a computing cluster obtained in 2010 with an NSF MRI grant. See Section 2.1.6 for more details. An array of student workstations is used for software development and non-CPU-intensive tasks all in the Physics Department research area. This cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can take more than a day before submission. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm. The University information technology staff maintains the cluster and provides the Red Hat Enterprise Linux software as part of its licensing agreement.

The University also supports undergraduate summer stipends and student travel. We have had 1-2, university-supported undergraduates working in our laboratory for each of the last three years. The student posters cited in Section 2.4 had travel support either from the University, the American Physical Society, or the current DOE contract. The University will support routine faculty travel to JLab at the level of ≈$4,500 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. The University supports routine faculty travel to JLab.

2.6 Summary

We now summarize our plan of work. We are preparing for JLab experiment E12-07-104 to measure the neutron magnetic form factor G_M^n after the 12 GeV Upgrade is complete, The Richmond group will develop software resources to simulate, reconstruct, and analyze data from CLAS12 and we will begin preparations to build the dual-cell target for E12-07-104. We will also pick up the analysis of the remaining data set from the E5 run period to extract G_M^n from existing CLAS6 data. The analysis of the fifth structure function in the $^2\mathrm{H}(\vec{e}, e'p)n$ reaction is far along and we will continue to push that work forward. The involvement of the PI in software planning will continue as the Collaboration considers ways to make the software enterprise more efficient. We request funds for a masters student to support this program and enhance our productivity and the intellectual environment for our undergraduate researchers and the Physics Department at Richmond. As usual, undergraduates will be involved in all phases of the program we describe here.

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[68] C. Musalo, J. Carbonneau, and G.P. Gilfoyle. Simulation of the CLAS12 Forward Electromagnetic Calorimeter. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2010.

3 Publications Since Last Review

*Refereed Journals (*denotes undergraduate co-author)*

The first set of publications are ones where Gilfoyle had considerable input as co-author.

1. V. Gyurjyan, D. Abbott, G.P. Gilfoyle, J. Carbonneau*, G. Heyes, S. Paul, C. Timmer, D. Wyegand, and E. Wolin. 'CLARA: A Contemporary Approach to Physics Data Processing', *Jour. of Phys. Open Access Conference Proc.*, 2011.

2. 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).

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. D. Keller *et al.* (CLAS Collaboration), "Electromagnetic decay of the Σ_0^* to $\Lambda\gamma$", Phys. Rev. D83, 072004 (2011).

2. R. Nasseripour *et al.* (CLAS Collaboration), "Coherent photoproduction of π^+ from 3He", Phys. Rev. C83, 034001 (2011).

3. H. Baghdasaryan *et al.* (CLAS Collaboration), "Tensor Correlations Measured in 3He(e,epp)n", Phys. Rev. Lett. 105, 222501 (2010).

4. B. Dey *et al.* (CLAS Collaboration), "Differential cross sections and recoil polarizations for the reaction $\gamma p \to K^+\Sigma^0$", Phys. Rev. C82, 025202 (2010).

5. M. Wood *et al.* (CLAS Collaboration), "Absorption of the omega and phi Mesons in Nuclei", Phys. Rev. Lett. 105, 112301 (2010).

6. X. Qian *et al.* (CLAS Collaboration), "Near-threshold photoproduction of phi mesons from deuterium", Phys. Lett. B 696, 338 (2011).

7. H. Avakian *et al.* (CLAS Collaboration), "Measurement of Single and Double Spin Asymmetries in Deep Inelastic Pion Electroproduction with Longitudinally Polarized Target", Phys. Rev. Lett. 105, 262002 (2010).

8. M. Osipenko *et al.* (CLAS Collaboration), "Measurement of the Nucleon Structure Function F2 in the Nuclear Medium and Evaluation of its Moments", Nucl. Phys. A 845, 1 (2010).

9. M.E. McCracken *et al.* (CLAS Collaboration), "Differential cross section and recoil polarization measurements for the gamma p to K+ Lambda reaction using CLAS at Jefferson Lab", Phys.Rev.C81:025201,2010.

10. Y. Ilieva *et al.* (CLAS Collaboration), "Evidence for a backward peak in the $\gamma + d \to \pi^0 + d$ cross section near the eta threshold", Eur.Phys.J.A43:261-267,2010.

11. S. Anefalos Pereira *et al.* (CLAS Collaboration), "Differential cross section of $\gamma n \to K^+\Sigma^-$ on bound neutron with incident photons from 1 to 3.6 GeV", Phys. Lett. B 688 (2010) 289-293.

12. M. Williams *et al.* (CLAS Collaboration), "Differential Cross Sections and Spin Density Matrix Elements for $\gamma p \to p\omega$", Phys. Rev. C 80, 065208 (2009).

13. M. Williams *et al.* (CLAS Collaboration), "Partial Wave Analysis of the Reaction $\gamma p \to p\omega$ and the Search for Nucleon Resonances", Phys. Rev. C, 80, 065209 (2009).

14. I.G. Aznauryan *et al.* (CLAS Collaboration), "Electroexcitation of Nucleon Resonances from CLAS Data on Single Pion Electroproduction", Phys. Rev. C 80, 055203 (2009).

15. M. Williams *et al.* (CLAS Collaboration), "Differential Cross Sections for the Reactions $\gamma p \to p\eta$ and $\gamma p \to p\eta'$", Phys. Rev. C 80, 045213 (2009). (2009).

16. M. Battaglieri *et al.* (CLAS Collaboration), "Photoproduction of $\pi^+\pi^-$ Meson Pairs on the Proton", Phys. Rev. D 80, 072005 (2009).

17. G. Gavalian *et al.* (CLAS Collaboration), "Beam Spin Asymmetries in DVCS with CLAS at 4.8 GeV", Phys. Rev. C 80, 035206 (2009).

18. R. Nasseripour *et al.* (CLAS Collaboration), "Photodisintegration of ^{4}He into p+t", Phys. Rev. C 80, 044603 (2009).

19. X. Qian *et al.* (CLAS Collaboration), "The Extraction of $\phi - N$ Total Cross Section from $d(\gamma, pK^+K^-)n$", Phys. Lett. B 680, 417 (2009).

20. M. Osipenko *et al.* (CLAS Collaboration), "Measurement of Unpolarized Semi-Inclusive π^+ Electroproduction off the Proton", Phys. Rev. D 80, 032004 (2009).

21. M. Dugger *et al.* (CLAS Collaboration), "π^+ Photoproduction on the Proton for Photon Energies from 0.725 to 2.875 GeV", Phys. Rev. C 79, 065206 (2009).

22. D.S. Carman *et al.* (CLAS Collaboration), "Beam-Recoil Polarization Transfer in the Nucleon Resonance Region in the Exclusive $ep \to e'K^+\Lambda$ and $ep \to e'K^+\Sigma^0$ Reactions", Phys. Rev. C 79, 065205 (2009).

23. M. Battaglieri et al. First measurement of direct $f_0(980)$ photoproduction on the proton. *Phys. Rev. Lett.*, 102:102001, 2009.

24. G. V. Fedotov et al. Electroproduction of $p\pi^+\pi^-$ off protons at $0.2 < Q^2 < 0.6\ GeV^2$ and $1.3 < W < 1.57\ GeV$ with CLAS. *Phys. Rev.*, C79:015204, 2009.

25. S. A. Morrow et al. Exclusive ρ^0 electroproduction on the proton at CLAS. *Eur. Phys. J.*, A39:5–31, 2009.

26. M. Nozar et al. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system. *Phys. Rev. Lett.*, 102:102002, 2009.

27. A. S. Biselli et al. First measurement of target and double spin asymmetries for polarized e- polarized p $\to$ e p pi0 in the nucleon resonance region above the Delta(1232). *Phys. Rev.*, C78:045204, 2008.

28. I. G. Aznauryan et al. Electroexcitation of the Roper resonance for $1.7 < Q^2 < 4.5 GeV^2$ in $ep \to en\pi^+$. *Phys. Rev.*, C78:045209, 2008.

29. J. P. Santoro et al. Electroproduction of $\phi(1020)$ mesons at $1.4 \leq Q^2 \leq 3.8$ GeV^2 measured with the CLAS spectrometer. *Phys. Rev.*, C78:025210, 2008.

30. M. H. Wood et al. Light Vector Mesons in the Nuclear Medium. *Phys. Rev.*, C78:015201, 2008.

31. Y. Prok et al. Moments of the Spin Structure Functions g_1^p and g_1^d for $0.05 < Q^2 < 3.0 GeV^2$. *Phys. Lett.*, B672:12–16, 2009.

32. R. Nasseripour et al. Polarized Structure Function $\sigma_{LT'}$ for $p(\vec{e}, e'K^+)\Lambda$ in the Nucleon Resonance Region. *Phys. Rev.*, C77:065208, 2008.

Technical Reports (denotes undergraduate co-author)*

1. G.P. Gilfoyle, M.Ungaro, J. Carbonneau*, M. Moog*, and and C. Musalo*, "Simulated CLAS12 Neutron Detection Efficiency in the Forward Time-of-Flight System", CLAS-NOTE 2011-015, Jefferson Lab, 2011.

2. G.P. Gilfoyle, M.Ungaro, J. Carbonneau*, M. Moog*, and and C*. Musalo, "Simulation of the Electromagnetic Calorimeter in CLAS12", CLAS-NOTE 2011-019, Jefferson Lab, 2011.

Proceedings and Abstracts

1. D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, D. Kaplan, H. Montgomery, S. Vigdor *et al.*, "Gluons and the quark sea at high energies: Distributions, polarization, tomography," [arXiv:1110.2770 [nucl-ex]].

2. G. P. Gilfoyle, "Few-body physics with CLAS," Few Body Syst. **50**, 15-22 (2011).

3. G. P. Gilfoyle. "Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium," Prepared for Exclusive Reactions at High Momentum Transfer IV, Jefferson Lab, 18-21, May 2010.

4. M. Moog and G.P. Gilfoyle. Simulating the Neutron Detection of the CLAS12 Detector. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2009.

5. M. Moog, J. Carbonneau, and G.P. Gilfoyle. Simulating the Neutron Detection Efficiency of the CLAS12 Detector. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2010.

6. C. Copos and G.P. Gilfoyle. Testing Analysis Algorithms for the $^2\mathrm{H}(\mathrm{e}, \mathrm{e}'\mathrm{p})\mathrm{n}$ Reaction. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2009.

7. J. Carbonneau and G.P. Gilfoyle. Development of a Computing Cluster At the University of Richmond. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2010.

8. C. Musalo, J. Carbonneau, and G.P. Gilfoyle. Simulation of the CLAS12 Forward Electromagnetic Calorimeter. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2010.

9. C. Musalo, J. Carbonneau, and G.P. Gilfoyle. Simulation of the CLAS12 dual hydrogen-deuterium target. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2011.

4 Principal Collaborators

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

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

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

Mac Mestayer	William Brooks	Bernhard Mecking
Lawrence Weinstein	Michael Vineyard	Andrei Afanasev
David Jenkins	Jeffrey Lachniet	Latifa Elouadrhiri
Sabine Jeschonnek	J.W. Van Orden	Hartmuth Arenhövel
John Arrington	Mark Ito	Eliot Wolin
Dennis Weygand	Kawtar Hafidi	Brian Quinn
David Abbott	Graham Heyes	Carl Timmer

The remaining members of the CLAS Collaboration are listed below.

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

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

5 Biographical Sketch: Dr. Gerard P. Gilfoyle

Degrees	Ph.D., University of Pennsylvania, 1985 - 'Resonant Structure in $^{13}C(^{13}C,^{4}He)^{22}Ne$', H.T. Fortune, adviser. A.B., cum laude, Franklin and Marshall College, 1979.
Experience	2008-present - Clarence E. Denoon Professor of Science, University of Richmond. 2004-present - Professor of Physics, University of Richmond. 2002-2003 - Scientific Consultant, Jefferson Laboratory. 1999-2000 - American Association for the Advancement of Science Defense Policy Fellow. 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. 1979-1985 - Research Assistant, University of Pennsylvania.
Research and Teaching Grants	2010-present - NSF MRI grant ($162,000). 1990-present - US Department of Energy ($1,560,000). 2010 - CLAS12 Software Workshop support, JSA/SURA Initiatives Fund ($7,500). 2009-2010 - JSA/SURA and Jefferson Laboratory sabbatical support. 2002-2003 - SURA and Jefferson Laboratory sabbatical support. 2001-2002 - National Science Foundation ($175,000). 1999-2000 - American Association for the Advancement of Science ($48,000). 1995-1997 - National Science Foundation($14,986). 1994-1995 - CEBAF Sabbatical Support ($24,200) 1992-1995 - National Science Foundation ($49,813). 1989-1991 - Research Corporation($26,000).
Selected Service	2006 - 2010 - Chair, Nuclear Physics Working Group, CLAS Collaboration. 2006 - present - CLAS Coordinating Committee. 2005 - Reviewer, National Science Foundation (Nuclear Physics). 2003 - present - Southeastern Universities Research Association Trustee. 2002 - present - Reviewer, CLAS Collaboration. 2002 - Reviewer, Civilian Research and Development Foundation. 2002 - 2003 - American Physical Society Task Force on Countering Terrorism. 2000 - 2006 - Chair, Department of Physics. 2000 - Reviewer, US Department of Defense. 1999 - Reviewer, Department of Energy EPSCoR Program. 1996 - Chair, review panel, National Science Foundation, Instrumentation and Laboratory Improvement Program.
Honors	2004 - Who's Who Among America's Teachers. 2003 - University of Richmond Distinguished Educator Award.

Selected Listing of Refereed Publications

1. 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).

2. 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).

3. M. Battaglieri, R. De Vita, V. Kubarovsky, *et al.*, (The CLAS Collaboration), 'Search for $\theta^+(1540)$ pentaquark in high statistics measurement of $\gamma p \to \overline{K}_0 K^+ n$ at CLAS', Physical Review Letters 96, 042001 (2006).

4. B. Mecking, *et al.*, (The CLAS Collaboration), 'The CEBAF Large Acceptance Spectrometer', Nucl. Instr. and Meth., **503**/3, 513 (2003).

5. G.P.Gilfoyle and J.A.Parmentola, 'Using Nuclear Materials to Prevent Nuclear Proliferation', Science and Global Security **9**, 81 (2001).

6. G.P.Gilfoyle, 'A New Teaching Approach to Quantum Mechanical Tunneling', Comp. Phys. Comm., **121-122**, 573 (1999).

7. G.P.Gilfoyle, M.S.Gordon, R.L.McGrath, G.Auger, J.M.Alexander, D.G.Kovar, M.F. Vineyard, C.Beck, D.J. Henderson, P.A.DeYoung, D.Kortering, 'Heavy Residue Production in the 215 MeV $^{16}O+^{27}Al$ Reaction', Phys. Rev., **C46**, 265(1992).

Selected Presentations

1. "Future Measurements of Elastic Electromagnetic Form Factors at Jefferson Lab", presented at PINAN11 in Marrakech, Morocco September 26, 2011.

2. "CLAS12 Software Readiness Review", presented at Information Technology for the 12 GeV Era - Internal Review, Jefferson Lab, May 20, 2011.

3. "Few-body physics with CLAS", presented at the 21st European Conference on Few-Body Problems in Physics, Salamanca, Spain, Aug 30, 2010.

4. "Precise Measurement of the Neutron Magnetic Form Factor", presented to the Physics Division at Argonne National Laboratory, June 1, 2009.

5. "Measuring the Fifth Structure Function in $D(\vec{e}, e'p)n$", poster presented at the Gordon Conference on Photonuclear Reactions, Tilton, New Hampshire, August 10-15, 2008.

6. "Review of QCD Processes in Nuclear Matter at Jefferson Lab", presented at the XVI Workshop on Deep Inelastic Scattering and Related Subjects", London, England, April 8, 2008.

7. "A High-Precision Measurement of G_M^n with CLAS", Workshop on Exclusive Reactions at High Momentum Transfer, Newport News, VA, May 22, 2007.

8. "Using Nuclear Materials to Prevent Nuclear Proliferation", colloquium presented at Thomas Jefferson National Accelerator Facility, Newport News, VA, March 7, 2001.

6 Student Tracking Information

The University of Richmond is a primarily undergraduate institution and the Physics Department has no graduate students.

7 Current and Pending Support

We have no pending proposals at this time.

By the end of this funding period we expect to have less than \$6000 remaining in equipment, travel and undergraduate stipends. We have been successful over the last three years at obtaining University funds for travel and for undergraduate stipends which allows us to enhance the program. Our undergraduates operate best when there is at least one experienced person in the group who can provide leadership and guidance to new students. We have been able to create such an environment by bringing students who just completed there first or second year at Richmond into the group while still being able to support the more experienced ones. We have had three or more students supported by our group each summer over the last years. We have also been able to support a computer science student during the academic year in 2011 to complete a project to add neutron reconstruction to the CLARA-based CLAS12 reconstruction code. See Section 2.1.2.

We expect that most of the remaining funds will be in equipment and travel (not undergraduate stipends). These funds will be used to primarily for travel to meetings for the PI and his students and for maintaining the computer laboratory at Richmond.

8 Facilities and Resources

8.1 University of Richmond Resources

The nuclear physics group at the University of Richmond is supported by a computing cluster obtained in 2010 with an NSF MRI grant. See Section 2.1.6 for more details. An array of student workstations is used for software development and non-CPU-intensive tasks all in the Physics Department research area. This cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can take more than a day before submission. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm. The University information technology staff maintains the cluster and provides the Red Hat Enterprise Linux software as part of its licensing agreement.

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

8.2 Proximity to Jefferson Lab

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

A Confirmation letter from the University of Surry

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Prof. Dr. Gerard Gilfoyle
Physics Department

University of Richmond,
VA 23173
USA

Dear Prof. Gilfoyle:

I am writing to express my full support of your DoE research grant application and also to confirm that, we would be delighted to place a Surrey MPhys research year student under your supervision at U. Richmond to work at J-Lab. As you know, the Surrey MPhys research programme has been running for more than 15 years. The students have completed 300 credits of undergraduate physics courses at Surrey before they begin their research dissertation. A total of 300 credits is the formal requirement for a bachelors degree (BSc) without honours at Surrey. The research year component, which includes a full written and assessed research dissertation plus an additional 6 Masters levels classes when they return from their research year, makes up the final 180 credits for their final honours Masters (MPhys) degree.

The MPhys students are rather selective at Surrey, both from the higher entry grades which are required for students to enter the programme from school and also in terms of the overall grades required for the first two years of undergraduate Physics studies at University. MPhys students are required to sustain at least an 'upper second class' grade in their Physics studies during the first two years of their undergraduate programme, which is equivalent to the academic requirement to be able to eligible for a UK Research Council PhD research scholarship following graduation.

As you know, a number of leading US and Canadian nuclear physics groups have hosted Surrey MPhys research students over the past decade, including the nuclear laboratories at Yale, Notre Dame, North Carolina, Rutgers/Oak Ridge National Laboratory and of course your department at Richmond under Prof. Beausang's supervision. The overall quality of the students can be gauged by the fact that two of these students have been honoured for their research by winning the UK's National Physics Student of the Year Award for their MPhys research project (2003 and 2006), with two more students being shortlisted for this award over the period. (This is an extremely competitive award for which all UK University physics departments take part.) In addition, Surrey MPhys students have co-authored more than 50 peer-reviewed research papers in nuclear physics over the last decade from their research project work.

The students for the 2013-14 research year cohort would be due to start their research projects from February 2013. Note, that there is no tuition fee costs for these research students (who remain registered as Masters students at Surrey during their research placement), but the host institution/group is expected to pay the research student a salary/stipend during their placement. I hope these few words clarify the main issues associated with the MPhys placement programme. I wish you the best of luck with your DoE research proposal and am delighted to give my full support to your aim of hosting a Surrey MPhys student to work with you on your project.

With my best regards

Professor Patrick Regan, MPhys Research Year Director, University of Surrey, UK

B Budget Justification

YEAR 1 (June 1, 2012 - May 31, 2013)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,000 whichever is smallest.

B.2 One master's student for five months (Jan-May, 2013) at an annual stipend of $26,200. In the Surry program the students' research year runs January to December. The dates for this contract are June 1 - May 31 of the previous year. The earliest we would expect for a masters student to arrive would by January, 2013 so five months of their research year would be covered in the first 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 per senior personnel for 10 summer weeks. This rate is the same as the University stipends.

C Fringe benefit rate is 8% for senior personnel and undergraduate summer stipends and 26% for the master's student.

D.1 Domestic travel:

1. $2100 - Round trip mileage charge for the master' student to travel to Richmond 2-3 times per month to work with the PI and his undergraduate researchers and attend the weekly seminars at Richmond.
2. $2000 - Travel expenses for the master's student to attend one conference to present their findings..
3. $2200 - Travel funding for shift taking for PI and students. Based on 12 shifts per year and three Collaboration meetings of about 4 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at $0.46 per mile. Note: routine faculty travel of this sort is covered by the University.
4. $4000 - Additional travel expenses for invited talks. Over the last three years Gilfoyle has given 1o invited talks including ones at domestic and international conferences. 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 = $10,300

G.1 - $2,403 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 21% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.

YEAR 2 (June 1, 2013 - May 31, 2014)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,000 whichever is smallest.

B.2 One master's student for seven months (Jun-Dec) at an annual stipend of $26,200 followed by a second student (Jan-May) for five months at the same rate. There are no tuition costs for this student. At Richmond they are classified as professional personnel.

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

C Fringe benefit rate is 8% for senior personnel and undergraduate summer stipends and 26% for the master's student.

D.1 Domestic travel:

1. $2100 - Round trip mileage charge for the master' student to travel to Richmond 2-3 times per month to work with the PI and his undergraduate researchers and attend the weekly seminars at Richmond.
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   Total = $10,300

G.1 - $2,106 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 21% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.

YEAR 3 (June 1, 2014 - May 31, 2015)

A.1 Senior personnel's summer salaries are 2/9's of their academic year salaries or $15,000 whichever is smallest.

B.2 One master's student for seven months (Jun-Dec) at an annual stipend of $26,200 followed by another student (Jan-May) for five months at the same rate. There are no tuition costs for this student. At Richmond they are classified as professional personnel.

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

C Fringe benefit rate is 8% for senior personnel and undergraduate summer stipends and 26% for the master's student.

D.1 Domestic travel:

1. \$2100 - Round trip mileage charge for the master' student to travel to Richmond 2-3 times per month to work with the PI and his undergraduate researchers and attend the weekly seminars at Richmond.
2. \$2000 - Travel expenses for the master's student to attend one conference to present their findings..
3. \$2200 - Travel funding for shift taking for PI and students. Based on 12 shifts per year and three Collaboration meetings of about 4 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at \$0.46 per mile. Note: routine faculty travel of this sort is covered by the University.
4. \$4000 - Additional travel expenses for invited talks. Over the last three years Gilfoyle has given 1o invited talks including ones at domestic and international conferences. 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 = \$10,300

G.1 - \$2,106 - Computer parts and repair (*e.g.*, office supplies, *etc* for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

I - Indirect costs: 53% of wages, salaries, and fringe benefits for the PI and undergraduates; 21% for the master's student who will spend more than 50% of their time away from the University of Richmond campus.