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 at higher energy. The research is part of the program at the Thomas Jefferson National Accelerator Facility (TJNAF). We are measuring components of the wave function of the simplest nucleus, the deuteron, and extracting the charge and magnetization distributions of the neutron where the hadronic picture still holds. We will push some of these measurements to higher energy to reveal the underlying quark-gluon substructure as part of the TJNAF 12-GeV Upgrade.

1 Project Introduction

This is a renewal application to support the University of Richmond electromagnetic nuclear physics research program in Hall B at the Thomas Jefferson National Accelerator Facility (JLab) using the CLAS detector. Dr. G.P. Gilfoyle is the principle investigator (PI). A list of our physics projects is shown in Table 1.

Title	Type
Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)	CLAS-Approved Analysis
Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium (Gilfoyle: spokesperson and contact person)	Letter-of-Intent LOI12-06-107
The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Electron-Neutron to Electron-Proton Scattering in Deuterium	Experiment E94-017
Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)	Proposal PR12-06-117

Table 1: Summary of primary physics interests of the Richmond group.

We now summarize our accomplishments in the two years since our last review. We are extracting the out-of-plane (or azimuthally dependent) structure functions of the deuteron using the $D(\vec{e}, e'p)n$ reaction measured during the E5 running period in CLAS in the range $Q^2 = 0.1-5.0$ (GeV/c)^2. We have completed event selection and kinematics corrections for all three sets of running conditions and extracted the asymmetry A'_{LT} in quasielastic kinematics proportional to the fifth structure function f'_{LT}. This structure function is the imaginary part of the LT interference and is sensitive to final state interactions and the NN interaction. A preliminary comparison with three theoretical calculations shows agreement with a model based on the Generalized Eikonal Approximation (GEA). Preliminary results were shown recently [1]. We have joined an effort to measure the magnetic form factor of the neutron G_M^n (JLab Experiment E94-017) which uses the same E5 data set. The analysis of two out of three sets of E5 running conditions is largely complete and is currently under Collaboration technical review [2]. We propose below to analyze the third data set. We also submitted a Letter-of-Intent to the Jefferson Lab Program Advisory Committee (PAC) to extend these measurements to higher Q^2 as part of the JLab 12-GeV Upgrade [3, 4]. The

Letter-of-Intent was approved in August, 2005 (LOI12-06-107) and we were encouraged to develop a full proposal [5]. We have proposed to investigate quark propagation in nuclear matter and the subsequent formation of hadrons by measuring the ratio of hadron production relative to deuterium and transverse momentum broadening. There are six experiments within the program and we are responsible for one of them along with K. Joo at the University of Connecticut; the analysis of the π^0, η, and η' channels. A proposal for this program was submitted and approved by the JLab PAC in August, 2006 (PR12-06-117) [6]. We continue to improve a computer code EXCLURAD for calculating radiative corrections to the $D(\vec{e}, e'p)n$ reaction [7, 8, 9, 10]. We have included an option so the user can essentially set a chosen value of the so-called fifth structure function (see Section 2.1.1) and study the impact on the radiative corrections. Gilfoyle was elected chair of the Nuclear Physics Working Group (one of three physics working groups in the Collaboration) in June, 2006 and his tenure as chair of Physics at the University of Richmond ended in May, 2006.

We now summarize our proposed plan of work for the next three years. We will complete our analysis of the fifth structure function f'_{LT} in quasielastic kinematics for all three sets of running conditions in the E5 data set. We are now generating simulations to investigate backgrounds and a CLAS Analysis Note is in preparation.[1] We will extract the other azimuthally-dependent structure functions, f_{TT} and f_{LT} in quasielastic kinematics and also push our analysis to higher energy transfer ν where the mix of different nucleonic effects is expected to change. We extract these structure functions using asymmetries described in Section 2. These measurements have the potential to establish a baseline for the hadronic model at low Q^2 which will enable us to more clearly see the onset of quark-gluon degrees of freedom at higher Q^2. We are taking on the analysis of the neutron magnetic form factor G_M^n in the low-Q^2 running conditions of the E5 data set (JLab Experiment E94-017) in the range $Q^2 = 0.1 - 2.5$ (GeV/c)^2. We will extract G_M^n using the ratio of $e-p$ to $e-n$ scattering coupled with knowledge of the other elastic electromagnetic form factors. This method has already been successful for the other two sets of running conditions in the E5 data set [2]. These data could have considerable impact on the experimental situation in this Q^2 range where there are inconsistencies among different data sets and a recent, suggested observation of the pion cloud. We will also propose the extension of these measurements to high Q^2 as part of the JLab 12-GeV Upgrade. The Letter-of-Intent mentioned above will be developed into a full proposal in the next year. This project will significantly extend our understanding of this fundamental quantity. During the next three years we will continue to develop the approved proposal to study quark propagation and hadron formation. As part of the Upgrade we are committed to support software development for the 12-GeV upgrade including event simulation of the components of the upgraded CLAS detector to guide the design of the detector and the development of the physics proposals. We will also enhance the radiative corrections code EXCLURAD and add new physics models to the program.

The personnel on this project will include Gilfoyle and a group of undergraduates. Gilfoyle will be on sabbatical during the third year of the proposal (2009-2010). During the last two years four students have worked in our group and presented their work at local and national meetings [11, 12, 13, 14, 15, 16, 17, 18, 19]. We also request funds to hire a high school science teacher who will contribute to our research enterprise and, in time, use his or her experiences to enhance their teaching and recruit more young people into science.

[1] The CLAS Collaboration requires a technical paper to be written, reviewed internally, and approved by the Collaboration before the journal paper is submitted for publication.

2 Project Description

2.1 Status of Current Projects

2.1.1 Out-of-Plane Structure Functions of the Deuteron

We are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e}, e'p)n$ to establish a baseline or benchmark for the hadronic model of nuclei to meet. The data were measured with the CLAS detector in Hall B at JLab (see Section 2.2 for more details). This baseline is necessary so that we can more clearly map the transition from hadronic to quark-gluon degrees of freedom at higher Q^2. The cross section for the reaction with a polarized beam can be written as

$$\frac{d\sigma^5}{d\omega d\Omega_e d\Omega_{pq}} = C\left(\rho_L f_L + \rho_T f_T + \rho_{TT} f_{TT} \cos\phi_{pq} + \rho_{LT} f_{LT} \cos 2\phi_{pq} + h\rho'_{LT} f'_{LT} \sin\phi_{pq}\right) \quad (1)$$

where C and the ρ_i are functions of the known electron parameters, h is the helicity of the electron beam, and ϕ_{pq} is the azimuthal angle of the ejected proton relative to the 3-momentum transfer $\vec{q}$. This 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. See Figure 1. These structure

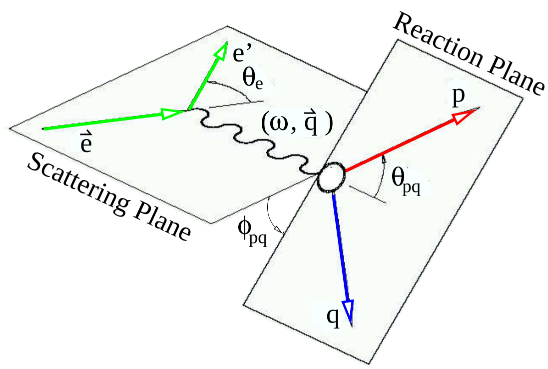

Figure 1: Kinematics of the $D(\vec{e}, e'p)n$ reaction.

functions depend on ϕ_{pq} and have not been extensively investigated in the past. They represent a model-independent measurement of a little-studied part of the deuteron cross section and probe its wave function. See Section 2.2.1 for a discussion of existing data.

In this status report we focus on our progress extracting the fifth structure function f'_{LT} (see Equation 1) which is the imaginary part of the LT interference. The structure functions are measured by forming asymmetries. This method was pioneered in the 1990s at Bates to study f'_{LT} using the asymmetry A'_{LT} defined as

$$A'_{LT} = \frac{\sigma^+_{90} - \sigma^-_{90}}{\sigma^+_{90} + \sigma^-_{90}} = \frac{\sigma'_{LT}}{\sigma_L + \sigma_T - \sigma_{TT}} \quad (2)$$

where the plus and minus superscripts refer to the beam helicity and the subscripts refer to ϕ_{pq}. The asymmetry in Equation 2 relies on small angle bins. To take full advantage of the large acceptance of the CLAS detector we form the asymmetries from the moments of the out-of-plane production.

To determine A'_{LT} we start with the $\sin\phi_{pq}$-weighted average for different beam helicities

$$\langle \sin\phi_{pq} \rangle_{\pm} = \frac{\int_0^{2\pi} \sigma^{\pm} \sin\phi_{pq} d\phi_{pq}}{\int_0^{2\pi} \sigma^{\pm} d\phi_{pq}} = \frac{1}{N_{\pm}} \sum_{i=1}^{N_{\pm}} \sin\phi_i \approx \pm \frac{A'_{LT}}{2} \tag{3}$$

where the pluses and minuses again refer to the beam helicity, $\sigma^{\pm}$ is the cross section in Equation 1 for different beam helicities, ϕ_i is ϕ_{pq} for an event, and $N_{\pm}$ is summed over all events of a particular beam helicity. The accuracy of the approximation in Equation 3 depends on the effect of the TT components of the cross section which are typically small. Once we have the weighted moments in Equation 3 for different beam helicities, we subtract the two to obtain A'_{LT}.

$$A'_{LT} = \langle \sin\phi_{pq} \rangle_{+} - \langle \sin\phi_{pq} \rangle_{-} \tag{4}$$

This reduces our sensitivity to background (see Section 2.2.1 below). Here we report on our results for quasi-elastic kinematics.

We are analyzing the E5 data set which consists of two beam energies (2.6 GeV and 4.2 GeV) with the CLAS torus set for normal polarity (electrons inbending) and another 2.6-GeV setting with reversed torus polarity (electrons outbending) to reach lower Q^2. The data cover the 4-momentum transfer range $Q^2 = 0.1 - 5.0$ $(\mathrm{GeV/c})^2$. Preliminary results for A'_{LT} are shown in Figure 2 as a function of the missing momentum $\vec{p}_m = \vec{q} - \vec{p}_p$ where $\vec{p}_p$ is the measured proton momentum. In the plane-wave impulse approximation this is the opposite of the initial momentum of the proton in the deuteron. These are the first data measured for this asymmetry in this Q^2 range. The results in

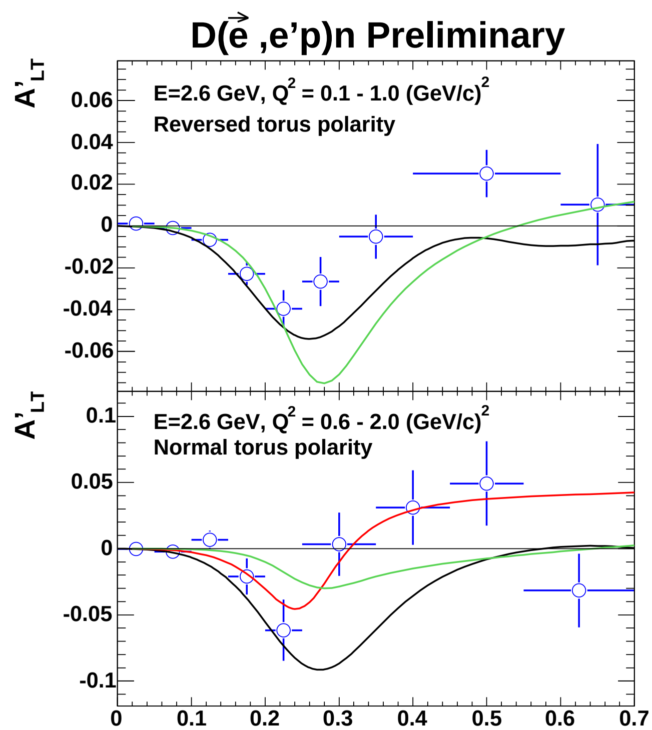

Figure 2: Preliminary results for the asymmetry A'_{LT} for the 2.6-GeV, E5 data sets. Curves are discussed in the text.

Figure 2 are for the two sets of running conditions at a beam energy of 2.6 GeV with opposite torus polarity. There is also a data set at 4.2 GeV, but the statistics for A'_{LT} are poor. Our preliminary results show we can observe small asymmetries with good precision in quasi-elastic kinematics. The black curves on each plot are from Arenhoevel [20] averaged over the CLAS acceptance. The Arenhoevel calculations have been successful at lower Q^2 and use the hadronic model approach with various corrections added [21]. Those calculations agree with the data in sign and magnitude for $p_m < 0.22$ (GeV/c), but overpredict the magnitude of the asymmetry at higher missing momentum. We also have preliminary calculations from Laget (green curves) and Jeschonnek (red curve) close to the average value of Q^2 for each data set [22, 23]. The preliminary calculation by Jeschonnek uses a generalized eikonal approach and reproduces our data.

The analysis of the structure function f'_{LT} for quasielastic kinematics is far along and will be completed in the near future. We have established the criteria for event selection including kinematics cuts and electron and hadron fiducial cuts and finished momentum corrections to improve the CLAS resolution for all three sets of running conditions. The fiducial cuts required fits to about 20,000 spectra. We have performed a variety of tests and consistency checks on the different E5 running conditions. We are now performing simulations of CLAS to ensure that we understand the detector response and to study any backgrounds. As mentioned above we expect the ratio in Equation 3 to be less sensitive to the acceptances. Our preliminary simulations support this expectation. This work is part of a CLAS Approved Analysis (see Table 1) and Gilfoyle is the spokesperson.[2] Preliminary results have been presented at conferences [1] and a CLAS analysis note is in preparation.

2.1.2 Magnetic Form Factor of the Neutron

The elastic electromagnetic form factors are the most basic observables that describe the internal structure of the proton and neutron. The differential cross section for elastic electron-nucleon scattering can then be calculated in the laboratory frame as [24]

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \left(G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right) \left(\frac{1}{1+\tau} \right) \tag{5}$$

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

$$\tau = \frac{Q^2}{4M^2} \qquad \text{and} \qquad \epsilon = \frac{1}{1 + 2(1+\tau)\tan^2(\frac{\theta}{2})} \tag{6}$$

where M is the nucleon mass and θ is the electron scattering angle. There are a total of four elastic form factors (electric and magnetic ones for each nucleon).

We are part of a broad assault on the four elastic nucleon form factors at Jefferson Lab [25, 26, 27]. All four elastic form factors are needed to untangle the different quark contributions and our focus is on the magnetic form factor of the neutron. For G_M^n we use the ratio of elastic $e-n$ to elastic $e-p$ scattering on deuterium. The method is based on the ratio

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2) \frac{\frac{{G_E^n}^2 + \tau {G_M^n}^2}{1+\tau} + 2\tau {G_M^n}^2 \tan^2(\frac{\theta}{2})}{\frac{{G_E^p}^2 + \tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2(\frac{\theta}{2})} \tag{7}$$

[2]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.

for quasielastic kinematics where deviations from the 'free ratio' assumption in the right-hand part of Equation 7 are parametrized by the factor $a(Q^2)$ which can be calculated from deuteron models and is close to unity at large Q^2. The ratio method is less vulnerable to systematic uncertainties than previous methods [2]. Equation 7 shows how the extraction of G_M^n depends on our knowledge of the other three nucleon form factors.

We have completed data collection and a significant portion of the analysis for a measurement of G_M^n in the range $Q^2 = 0.5 - 5.0$ (GeV/c)^2 [28, 2]. Preliminary results are shown in Figure 3. These are the results from the E5 running period (the same experiment as the one described in

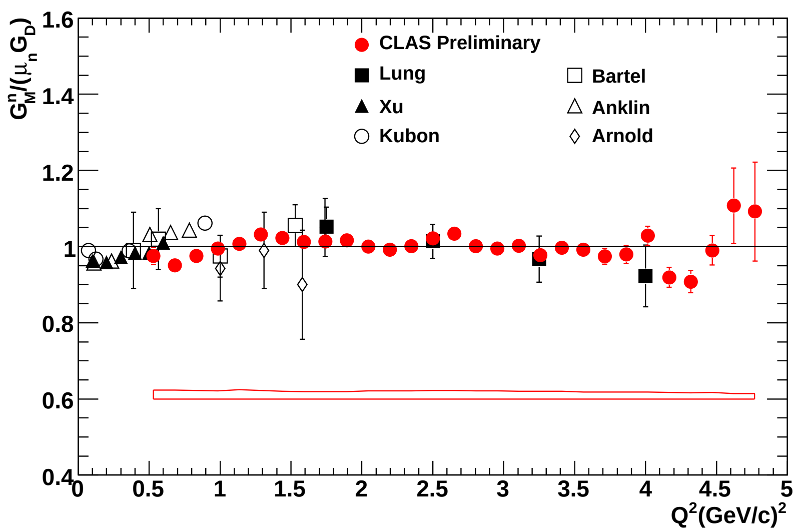

Figure 3: Selected results for the neutron magnetic form factor G_M^n in units of $\mu_n G_D$ as a function of Q^2. See Reference [2] and references therein.

Section 2.1.1) for two electron beam energies (2.6 GeV and 4.2 GeV) with the CLAS toroid having standard polarity (electrons inbending). The reversed polarity (electrons outbending) data at 2.6 GeV is still being analyzed. The data are plotted as the ratio to $\mu_n G_D$ where μ_n is the neutron magnetic moment and G_D is calculated in the dipole approximation. The data are consistent with G_D for $Q^2 > 1.0$ (GeV/c)^2. There are signs of disagreement with previous measurements for the results below 1 (GeV/c)^2. These results have sparked considerable interest from the theoretical community. A comparison with some of those calculations can be found in Ref [2]. A CLAS analysis note has been written and is under collaboration review. We have been part of the E5 analysis group for over four years and have provided a number of services to the group like radiative corrections. We are now developing a proposal for beam time as part of the physics program for the JLab, 12-GeV Upgrade. We have submitted a Letter-of-Intent to the JLab Program Advisory Committee (PAC) to make the same measurements at higher Q^2 as part of the physics program for the JLab 12-GeV Upgrade.[3] The Letter-of-Intent was approved by the PAC in August, 2006 and we have been 'encouraged to develop a full proposal' [4, 5]. Gilfoyle is co-spokesperson and contact person for the Letter-of-Intent and will play the same role for the proposal.

[3] A Letter-of-Intent is a preliminary proposal for beam time at JLab. It provides an opportunity for researchers to get feedback from the PAC on the quality of their idea before they make the large investment of time and effort required to produce a full proposal.

2.1.3 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 quantitatively is an essential goal of modern nuclear physics. The subject can be investigated by striking one of the quarks with a photon and stretching out the color string tying it to its neighbors. The color string stretches until $q\bar{q}$ pairs tunnel up from the vacuum, thwarting the struck quark's attempt to escape to isolation. Unfortunately, the real picture with full QCD is more complicated than this simple picture and experimental information is necessary to guide models of hadronization.

We have proposed a broad program of measurements and analyzes to determine the mechanisms of confinement in forming systems as part of the JLab 12-GeV Upgrade. This proposal builds on lessons learned at lower energy for the analysis of the EG2 run period at JLab. The experimental technique employs nuclei as analyzers of hadronization processes. The ratio of hadrons produced relative to the production from deuterium (hadronic multiplicity ratio R_M^h) and transverse momentum broadening Δp_T^2 are the two primary observables. These quantities are known to be sensitive to different kinematic regimes as well as the average distance through the nuclear medium. A proposal for this program was submitted and approved by the JLab PAC in the summer of 2006 [6]. Gilfoyle is a co-spokesperson on the proposal. The document describes not a single experiment, but a wide program of measurements and analyzes which share a common set of running conditions. Gilfoyle is responsible for analysis of the π^0, η, and η' channels along with Dr. K. Joo from the University of Connecticut.

2.1.4 Technical Projects and CLAS Collaboration Service

The measurements of the nuclear reactions described above are all subject to radiative corrections. We continue to develop a computer code called DEEP_EXCLURAD for calculating these corrections for the $D(e, e'p)n$ reaction. Radiative corrections are usually calculated using the formalism originally developed by Schwinger and Mo and Tsai [29, 30], but that approach does not account for the alteration of the phase space in exclusive reactions and it does not include the full set of structure functions we are studying here. We describe our approach to this problem in CLAS Note 2005-022 [7]. Since the publication of Reference [7] we have added another option so the user can set the value of A'_{LT} to investigate the effect of the fifth structure function on radiative corrections. Part of the appeal of using this asymmetry is that it reduces the sensitivity to radiative corrections. We found this assumption to be accurate. This code is available to the Collaboration (and anyone else) on the web [8].

Gilfoyle continues to fulfill his service role in the Collaboration. In the last two years he has served on review committees for four CLAS-Approved Analysis proposals (one as chair), two CLAS Analysis Note reviews (one as chair), and on an ad hoc review committee of a paper that was published in Physical Review D [31]. We maintain a 53-node supercomputing cluster in our laboratory at Richmond that is available to other collaboration members. In June, 2006 Gilfoyle was elected chair of the Nuclear Physics Working Group. He will be responsible for organizing reviews of papers, analysis notes, PAC proposals, *etc.* We also note here that his tenure as chair of Physics at Richmond ended in May, 2006.

2.2 Plan of Work

The research effort in nuclear physics is part of the program at the Thomas Jefferson National Accelerator Facility (TJNAF or JLab) in Newport News, VA. The primary goal of TJNAF is to reveal the quark and gluon structure of protons, neutrons, and atomic nuclei and to deepen our understanding of matter and, in particular, the confinement of quarks. In this section we describe the experimental environment and the proposed physics programs.

TJNAF is a unique tool for basic research in nuclear physics. The central instrument is a superconducting electron accelerator with a maximum energy of 4-6 GeV, a 100% duty cycle, and a maximum current of 200 μA. The electron beam is used simultaneously for scattering experiments in three halls that contain complimentary experimental equipment. Our research is done in Hall B with the CEBAF Large Acceptance Spectrometer (CLAS). This device is a large (45-ton), toroidal, multi-gap magnetic spectrometer with nearly full solid angle coverage. See Figure 4. A toroidal

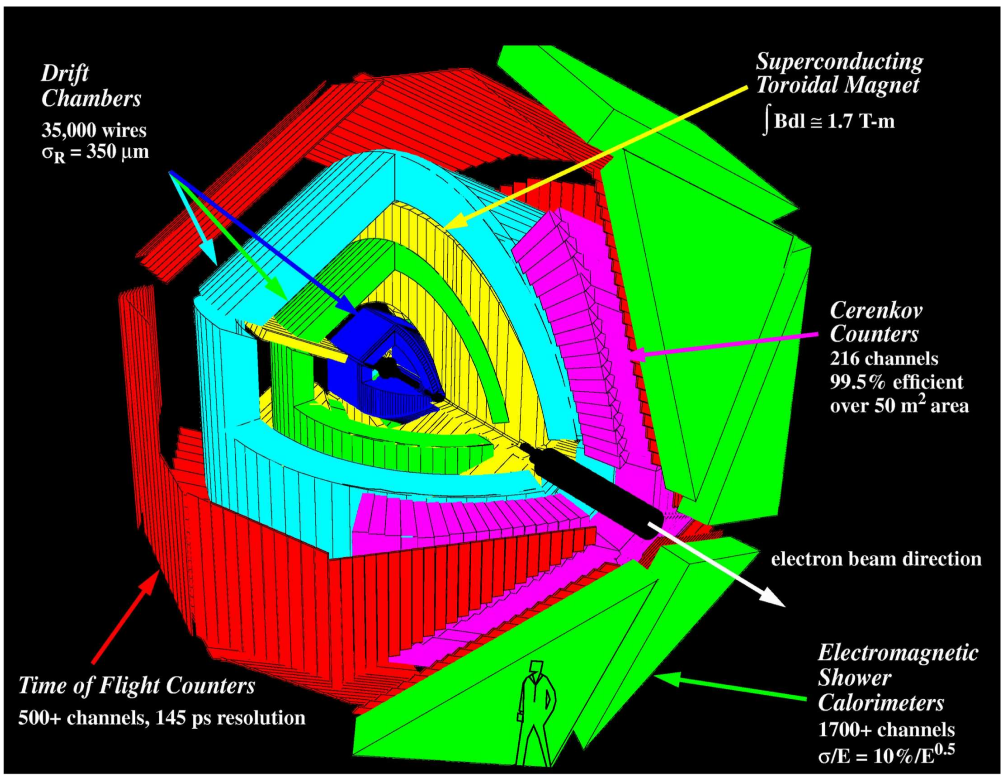

Figure 4: The CLAS detector.

magnetic field is generated by six iron-free superconducting coils. The particle detection system consists of drift chambers [32] to determine the trajectories of charged particles, Cerenkov detectors [33] for the identification of electrons, scintillation counters [34] for time-of-flight measurements, and electromagnetic calorimeters [35] to identify electrons and to detect photons and neutrons. The six segments are instrumented individually to form six independent spectrometers. Together there are about 33,000 detecting elements. The CLAS detector is capable of acquiring approximately 1 terabyte of data per day. It was constructed and is operated by an international collaboration consisting of thirty-six institutions. The Richmond group has been part of the CLAS Collaboration since its inception.

2.2.1 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 relative importance of relativistic corrections (RC), final-state interactions (FSI), meson-exchange currents (MEC), and isobar configurations(IC) is only now beginning to be studied [36]. These measurements complement an effort on the theory side to clarify our understanding of the hadronic picture of the deuteron. See 'The Deuteron Benchmarking Project' in Ref [37].

This project is consistent with the goals of the Nuclear Science Advisory Committee (NSAC) Long-Range Plan [38] and performance measures [39]. The deuteron is the simplest nucleus and a central testing ground for our understanding of the NN force. This project will provide unique measurements of little-studied portions of the deuteron wave function and establish a baseline for the hadronic model to meet so deviations at higher Q^2 can be attributed to quark-gluon effects with greater confidence. This is an important step in 'understanding the structure of light nuclei both in terms of nucleons at low energy and in terms of quarks and gluons at high energy' (see section on hadronic physics in Ref[39]). These are goals enunciated in the NSAC Long-Range Plan, its performance measures, and the JLab Program Advisory Committee (PAC)[38, 39, 40].

As mentioned in Section 2.1.1 we are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e}, e'p)n$ with CLAS. See Equation 1 and Figure 1 in Section 2.1.1 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 f'_{LT}, f_{LT}, and f_{TT} (see Equation 1). 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. The large acceptance of CLAS gives us the capability of accessing a wide range of Q^2 and energy transfer ν.

The methodology used to determine the structure functions is to form asymmetries from the weighted moments of the ϕ_{pq} distributions. We described this technique in Section 2.1.1 for A'_{LT} and analogous methods will be used for the other two ϕ_{pq} dependent structure functions A_{LT} for f_{LT} and A_{TT} for f_{TT} (see Equation 1) which are sensitive to different mixtures of nucleonic phenomena. Our preliminary results for these asymmetries reveal magnitudes as large as 0.8 with good statistical precision out to a missing momentum of $p_m \approx 0.7\ GeV/c$. However, these results are more sensitive to systematic uncertainties than A'_{LT} because they are not helicity dependent (see discussion on background asymmetries in the next paragraph and Ref [41]) and will have to be simulated more carefully. We are now making these calculations.

Background asymmetries can distort the physics asymmetries we are trying to measure. If the acceptance has a sinusoidally varying part, then one can show that Equation 3 in Section 2.1.1 becomes

$$\langle \sin \phi_{pq} \rangle_{\pm} \approx \pm \frac{A'_{LT}}{2} + \alpha \tag{8}$$

where α is the background term. Subtracting the moments for the different beam helicities cancels this background term (see Equation 4). Adding the two moments enables us to study the background for this asymmetry. We have used this subtraction technique in extracting A'_{LT} and are using the background asymmetry to gain insight into the source of the background for all three sets of E5 running conditions. Note, the simulations play a more important role in measuring A_{TT} and A_{LT} because they are not dependent on beam helicity.

We have been working with several theory groups to understand what our data is telling us. Recall Figure 2 which made a preliminary comparison among calculations from Arenhoevel, Laget, and Jeschonnek. The GEA calculation by Jeschonnek reproduces our data at $\mathrm{Q}^2 \approx 1$ (GeV/c)^2. Figure 5 demonstrates what else we may learn from A'_{LT}. The curves show the effect of different

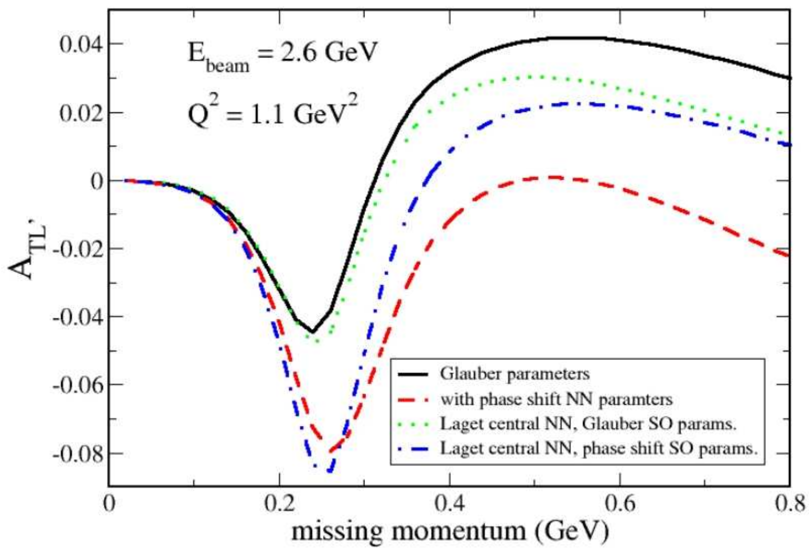

Figure 5: Comparison of different NN parameterizations for A'_{LT} [23].

NN parameterizations on the fifth structure function asymmetry A'_{LT}. The black curve in Fig 5 corresponds to the red curve from Jeschonnek in Figure 2. The red and blue curves in Figure 5 use a different for the NN force and predict too deep a minimum in A'_{LT}. Our data can discriminate between the different NN parameterizations (compare Figures 2 and 5).

We now discuss the present state of knowledge of these out-of-plane structure functions of the deuteron. Existing measurements of A'_{LT} are sparse. For quasi-elastic kinematics they have only been made at $Q^2 = 0.22$ (GeV/c)^2 and $Q^2 = 0.13$ (GeV/c)^2 at Bates [42, 43, 44]. An example of the results is shown in Figure 6. That work demonstrated the feasibility of out-of-plane measurements and the calculations show that relativity already plays a significant role even at this value of Q^2 [20]. The effect of final-state interactions is dramatic in Figure 6. The double-dot-dashed line at $A'_{LT} = 0$ is from a Plane-Wave Born Approximation calculation which does not include FSI. In general, f'_{LT} is non-zero only in the presence of final-state interactions. The other calculations include FSI and they are all significantly different from zero. Beyond quasi-elastic kinematics, there is a single measurement at $\mathrm{Q}^2 = 0.15$ (GeV/c)^2 in the dip region [45]. The results for A'_{LT} again reveal the importance of FSI, but limited statistics make further conclusions difficult.

The situation is little different for observations of the transverse-transverse asymmetry A_{TT}. These experiments do not necessarily require out-of-plane measurements, but this portion of the cross section must be separated from the larger contributions of f_L, f_T, and f_{LT} for reactions lying in the scattering plane. Three measurements in quasi-elastic kinematics have been made at Tohoku ($\mathrm{Q}^2 = 0.013$ (GeV/c)^2), NIKHEF ($\mathrm{Q}^2 = 0.21$ (GeV/c)^2), and Bates ($\mathrm{Q}^2 = 0.22$ (GeV/c)^2) [42, 46, 47]. The lowest Q^2 measurements agree with a non-relativistic calculation, but the uncertainties on all the data sets make it difficult to distinguish MEC, IC, FSI, and RC effects. There is a clear need here to reduce the uncertainties and extend the measurements out to larger missing

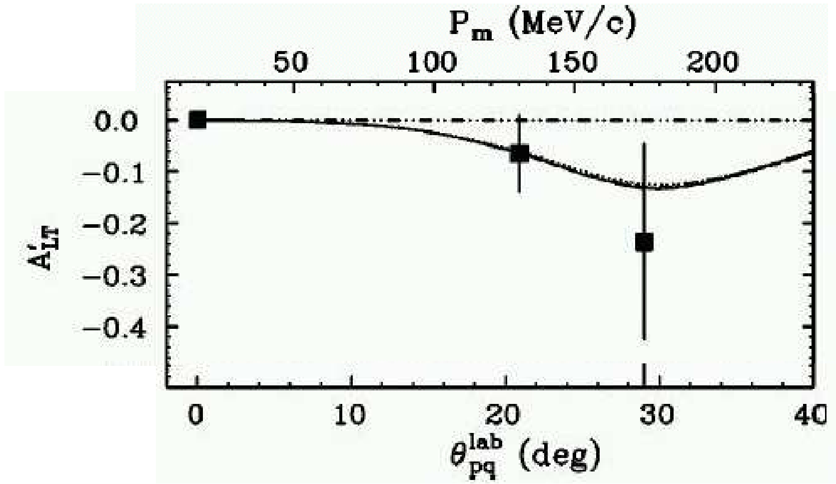

Figure 6: Measurements of f'_{LT} and its associated cross section and asymmetry from Reference [42] at $Q^2 = 0.13$ (GeV/c)^2.

momentum or θ_{pq}^{cm} where the calculations diverge. For dip kinematics, there is a single measurement at $Q^2 = 0.15$ (GeV/c)^2 [45]. A calculation that included FSI, MEC, IC, and RC reproduced the limited data set.

The longitudinal-transverse interference structure function f_{LT} has been measured several times and with greater precision than the other two structure functions above. At the lowest $Q^2 = 0.013$ (GeV/c)^2 the data are reproduced by a non-relativistic calculation while at the highest ($Q^2 = 1.2$ (GeV/c)^2) the relativistic calculations of the asymmetry are preferred [46, 48]. Between these two extremes, the situation is less clear. For example, some calculations favor relativistic corrections [49] while others at nearby Q^2 favor a non-relativistic calculation over a relativistic one [50, 51]. A recent JLab measurement supported inclusion of relativistic effects [52]. For dip kinematics at $Q^2 = 0.15$ (GeV/c)^2 a calculation including FSI, MEC, IC, and RC reproduced the limited data set [45].

This analysis project will complement other experiments at Jefferson Lab. Experiment E01-020 has two parts made up of two previous proposals: PR-01-007 (formerly E94-004, W.Boeglin spokesperson and contact) and PR-01-008 (P.Ulmer spokesperson and contact). Data collection for this experiment was completed in fall, 2002 in Hall A and the analysis is nearing completion. The focus here is on in-plane measurements of the $D(e, e'p)n$ reaction to extract f_{LT} (using a Rosenbluth separation technique) which will make an interesting comparison with our measurement of A_{LT}. A second goal of this experiment is to measure angular distributions to study FSI, MEC, and IC.

In the period for this proposal, we will complete the analysis of the f'_{LT} results and move on to the other two structure functions f_{LT} and f_{TT} in quasielastic kinematics using similar analysis methods. This is a unique opportunity to measure the three, out-of-plane, ϕ_{pq}-dependent, structure functions in a model-independent way from a single experiment that covers a large Q^2 range under a common set of experimental conditions. Once that analysis is complete, we will investigate higher energy transfer (*i.e.*, the 'dip' region). These other structure functions and kinematic regions are sensitive to different mixtures of the nucleonic phenomena being studied here. We have a unique chance here to untangle these different effects and establish a hadronic baseline to more clearly see the transition to quark-gluon degrees of freedom.

2.2.2 Magnetic Form Factor of the Neutron

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. The expression for the differential cross section can be found in Equation 5 in Section 2.1.2. We are part of a wide effort to measure the four elastic nucleon form factors at Jefferson Lab [25, 26, 27]. All four elastic form factors are needed to untangle the different quark contributions and our focus is on the magnetic form factor of the neutron. Measuring the elastic form factors like G_M^n is an explicit goal of NSAC's Long Range Plan for nuclear physics (see Chapter 2 of Ref [38]). That report states that understanding the structure of the proton and neutron is one of the main challenges facing nuclear physics and 'Connecting the observed properties of the nucleons with the underlying theoretical framework provided by QCD is one of the central problems of modern science' [38]. Our role in the G_M^n project is twofold. First, we are developing a proposal for beam time as part of the physics program for the JLab, 12-GeV Upgrade. A Letter-of-Intent to the JLab PAC in summer, 2006 was approved and we were 'encouraged to develop a full proposal' [5]. Second, we have taken on the task of analyzing the 2.6-GeV, reversed torus polarity (electrons outbending) data from the E5 running period. The goal is to extract G_M^n using the same methods developed for the other sets of running conditions at 2.6 GeV and 4.2 GeV (both have normal torus polarity with electrons inbending).

The current status of our understanding of G_M^n at lower Q^2 is shown in Figure 3 in Section 2.1.2 where G_M^n is scaled by the dipole form factor $G_D(Q^2) = 1/(1 + Q^2/\Delta)^2$ and $\Delta = 0.71$ GeV^2. The parameter Δ is interpreted as the square of the effective meson mass. We focus here on $Q^2 > 1.0$ GeV^2 where the neutron magnetic form factor agrees with the dipole form within 5-10%. This agreement can be qualitatively understood as a virtual photon interacting with the nucleon after the photon has fluctuated into a vector meson. There are, however, deviations from the dipole form that invite investigation. Some of the data have large error bars due largely to uncertainties in subtracting the contribution of the proton in these measurements using inclusive quasielastic scattering on deuterium [25]. The more precise measurements including the recent work by Lachniet, *et al.* and our E5 group (the red circles in Figure 3) [2, 28] and others [53, 54, 55, 56] use a ratio method which is described below.

Measuring G_M^n at higher Q^2 will shed light on important questions in hadronic physics. At asymptotically large Q^2, the elastic nucleon form factors can be rigorously calculated in perturbative QCD (pQCD) where the small wavelength of the virtual photon ensures that the quark substructure of the nucleon can be resolved [57]. It is assumed the nucleons can be treated as bound systems of point-like quarks governed by the properties of the strong interaction. Dimensional scaling predicts that only valence quarks will be important and those quarks interact via a hard-scattering process. These calculations reproduce the Q^2 dependence of the proton magnetic form factor for $Q^2 > 10$ GeV^2. The transition from the low-Q^2 dipole form to the pQCD regime is still unclear. Evidence from recent Jefferson Lab experiments and others suggest that non-perturbative effects still dominate the form factors for $Q^2 < 10$ GeV^2. For example, the Q^2 dependence of the ratio $\mu_p G_E^p / G_M^p$ is expected to be constant in pQCD, but surprising Jefferson Lab measurements of this ratio revealed significant Q^2 dependence up to $Q^2 \approx 5.0$ GeV^2 [58, 59, 60]. Higher Q^2 investigations show evidence of scaling behavior, consistent with predictions of quark dimensional scaling and perturbative QCD [58]. The elastic nucleon form factors are a fundamental challenge for lattice QCD calculations. Full calculations are still beyond our reach so existing ones use different approximations like quark masses much higher than the physical ones[61]. Extrapolations are then made to the physical quark mass region. Some success has been achieved in reproducing the shape of the Q^2 dependence of G_M^n for $Q^2 < 1.0$ GeV^2, but the higher Q^2 region remains new territory [61]. Recent theoretical work has led to the development of generalized parton distributions (GPDs) where form factors and structure functions can be simultaneously embedded. These distributions hold the promise of developing a three-dimensional image (two spatial and one momentum coordinate) of the nucleon. They have 'tremendous potential to provide a quantitative description of the quark motion inside hadrons' [62]. GPDs are typically studied via deeply virtual Compton scattering or real Compton scattering at high momentum transfer. However, the elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) are key constraints on GPDs. The lowest moments of the GPDs multiplied by the appropriate quark charges and summed over all quark flavors recover the form factors [63]. These sum rules hold for all values of Q^2 from zero to infinity. Measuring the nucleon form factors complements other proposed 12-GeV programs to measure deeply virtual exclusive (DVE) reactions at low momentum transfer $|t|$. The form factors connect to the GPDs at high $|t|$ (= Q^2 for elastic scattering) and so high-Q^2 data are needed to obtain the structure of the nucleon at small transverse distances [73].

We note that the effort to measure G_M^n in the range Q$^2 = 2-14$ GeV^2 is part of a larger Jefferson Lab program to increase our understanding of all four nucleon form factors and express them in terms of common GPDs. All four elastic form factors are needed to untangle the different quark contributions. However, at high Q^2 there is precise data only for the proton. The G_M^p data extend out to Q$^2 = 30$ GeV^2 while the G_M^n data in Figure 1 are just now being extended to Q$^2 = 4.5$ GeV^2 (red circles in Figure 3 from Lachniet, *et al.* [2]). With the 12-GeV upgrade of CEBAF, G_E^p/G_M^p and G_M^n can be measured up to Q$^2 \approx 14$ GeV^2 and for G_E^n up to Q$^2 = 5$ GeV^2 [73]. Figure 7 shows the expected Q^2 coverage and uncertainties that were presented in the Letter-of-Intent. We will expand the Q^2 range by almost a factor of three with uncertainties of a few percent. We will use many of the same experimental methods as our previous measurements and the overlap evident in Figure 7 with the E5 results provides us with an important cross check. A Letter-of-Intent was also recently approved by the JLab PAC to measure G_E^p/G_M^p in Hall C with the upgraded accelerator (LOI12-06-103). This elastic nucleon form factor program will be part of a 'great leap forward in our knowledge of hadron structure' [73].

As mentioned above, we will also take up the analysis of the existing, 2.6-GeV, reversed-torus-polarity data set from the E5 running period. These data cover the range Q$^2 = 0.1-1.0$ (GeV/c)^2. They overlap with our 2.6-GeV, normal-torus-polarity data set and with the results from several other groups. See Figure 3. There are disagreements between our data and some of the previous measurements and our low-Q^2 data could help sort out the experimental situation. At the same time, some recent efforts by Friedrich and Walcher [64] to re-analyze the low-Q^2 data for all four quasielastic, nucleon form factors suggests that a structure they observe at Q$^2 \approx 0.2$ (GeV/c)^2 in all the elastic form factors is due to the pion cloud. Recent measurements from BLAST [65] have shown structure in this Q^2 region ($\approx 0.1-1.0$ (GeV/c)^2) and additional theoretical work supports the observation of the pion cloud [66, 67]. There are hints of a bump in the ratio G_e^p/G_M^p from polarization measurements in a recent Hall A experiment [68]. However, others disagree. The observation of a structure near Q$^2 \approx 0.2$ (GeV/c)^2 contradicts what is known from chiral perturbation theory and dispersion relations [69]. Our low-Q^2 CLAS data reach down into this Q^2 range and would overlap with the bump observed in Ref [64]. We expect statistical and systematic uncertainties of about 2% each and the E5 data set has abundant overlaps and consistency checks to ensure the quality of the results. This is an excellent opportunity to improve our understanding of nucleon structure with data we already have in hand.

We will use the ratio R of $e-n$ to $e-p$ scattering from a deuterium target to measure G_M^n. The technique is based on Equation 7 in Section 2.1.2 which shows that knowledge of R, nuclear correction factors $a(Q^2)$, and the other elastic, nucleon form factors will enable us to extract G_M^n. To determine G_M^n we calculate the corrections $a(Q^2)$ in Equation 7 with existing models [2]. The

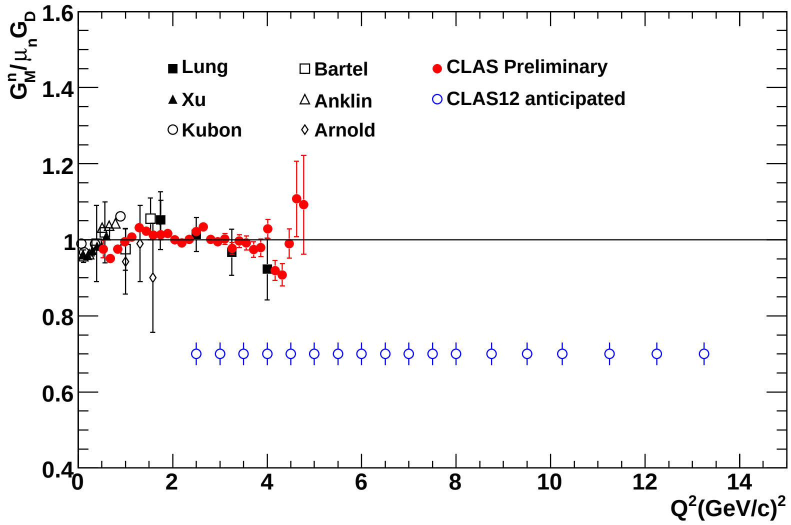

Figure 7: Results of G_M^n analysis (red points) and predictions for the 12-GeV Upgrade (blue open points) with the upgraded CLAS detector (CLAS12).

proton form factors are precisely known and the neutron's electric form factor G_E^n is typically small. By taking ratios in Equation 7 we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction efficiency, trigger efficiency, the deuteron wave function, and radiative corrections. 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, hydrogen-deuterium, target cell was used in the E5 running period (and is proposed for the higher Q^2 measurement for the 12-GeV Upgrade). We use the $ep \rightarrow e'\pi^+n$ reaction as a source of tagged neutrons to measure the neutron efficiency simultaneously with data collection on deuterium. The neutrons are detected in two, overlapping measurements with both the electromagnetic calorimeter (EC) and the time-of-flight (TOF) system in CLAS (or the upgraded CLAS detector called CLAS12). The TOF measurement provides a useful cross check on the EC measurement. 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 and assuming quasielastic scattering from one of the nucleons in deuterium. We then use the electron kinematics to determine if a quasielastic proton or neutron would fall in the CLAS acceptance. If so, then we search for a proton or neutron in the predicted location. Corrections for Fermi motion of the nucleons bounds in the deuteron are calculated in our simulation. Identification of quasielastic events on deuterium at high Q^2 is one of the challenges in the 12-GeV-Upgrade experiment. In addition to cuts on the recoil mass of the target, we will also constrain the angle between the detected nucleon and 3-momentum transfer $\vec{q}$. This method has proved successful in our analysis of the E5 data.

During the period of this proposal we will develop the Letter-of-Intent into a full proposal for submission next year. The PAC has approved the Letter-of-Intent and encouraged us to do that. We will also perform the analysis of the 2.6-GeV, reversed field data described above. We will be working with M.F. Vineyard (Union College) and W.K. Brooks (JLab), the two spokespersons on the original G_M^n proposal (E94-017). The analysis of these data and for the high-Q^2 G_M^n proposal are similar so we can make efficient use of our time and resources.

2.2.3 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and its understanding is a central challenge in nuclear physics. We propose to 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 the 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 consistent with the NSAC Long-Range Plan. We will learn about the nature of quark confinement and provide a testing ground for QCD. Understanding confinement and QCD will help answer one of the five main questions posed in the NSAC Long-Range Plan; 'What is the structure of the nucleon?' [38].

The first measurements of the hadronization length go back to the 1970's at SLAC with confirmation of the phenomenon following at FermiLab and the EMC experiment. These groups studied the attenuation of the production of hadrons on nuclear targets relative to deuterium and were able to conclude that hadronization was taking place inside the nucleus [70, 71, 72]. The results encouraged the development of new experiments at HERMES and JLab. The HERMES Collaboration has published a large set of data on the ratio of hadron production relative to deuterium ($\pi^{\pm}$, π^0, $K^{\pm}$, p, $\overline{p}$) from ^{14}N and Kr targets. Their results confirm predictions about the hadron production and its sensitivity to different kinematic quantities like z, ν, Q^2, and p_T^2. More recent measurements in CLAS during the EG2 running period promise to significantly improve our understanding of the phenomena. The data quality in EG2 is high enough that multiplicity ratios can now be measured with smaller statistical uncertainties and the sensitivity to kinematic variables can be studied. These data are still undergoing analysis, but preliminary results exhibit significant attenuation with the mass of the target nucleus and show trends similar to the HERMES data.

The experimental method we will use relies on the atomic nucleus as an analyzer of the hadronization process. The ratio of hadrons produced relative to the production from deuterium (hadronic multiplicity ratio R_M^h) and transverse momentum broadening Δp_T^2 are the two primary observables. These are known to be sensitive to different kinematic regimes as well as the average distance through the nuclear medium. We have proposed to measure these quantities in deep inelastic kinematics over 5-6 target nuclei and for 15-20 different hadronic channels. These will enable us to study the systematic behavior of the hadronization process and determine the mechanism of the the formation of the hadrons. A proposal for this experiment as part of the physics program for the JLab 12-GeV Upgrade was submitted and approved by the JLab PAC in the summer of 2006 [6]. Gilfoyle is a co-spokesperson on the proposal and is responsible for analysis of the π^0, η, and η' channels along with Dr. K. Joo from the University of Connecticut.

During the period of this grant we will begin work on the simulation of events in the upgraded CLAS detector (CLAS12) to further develop this idea. We are committed to development projects for the JLab 12-GeV Upgrade and will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction. Event simulation is an essential aspect of the design of CLAS12 and eventual precision of the detector. For many experiments, the quality of the results will be limited by systematic uncertainties instead of statistical ones. Accurate, precise calculations of the CLAS12 acceptance and response are important to keep those systematic uncertainties small. To do that we expect to generate about four times as much simulated, Monte Carlo data as CLAS12 collects. The CLAS12 simulation will produce data more slowly than the detector itself so the contribution of university groups to this effort is essential. The same issues that arise in designing the physics experiments also arise in the design and prototyping phase of the project we are just entering. First beams are not expected until well into the next decade, but this work has already begun. Dr. Joo is part of the effort to develop the calorimeters for CLAS12 and Gilfoyle is committed to work on software including event generation.

2.2.4 Technical Projects and CLAS Collaboration Service

During the period of this proposal we will continue work on radiative corrections for exclusive reactions on the deuteron. We have modified the radiative correction program DEEP_EXCLURAD for the $D(\vec{e}, e'p)n$ case. See Section 2.1.4 for more details. During the period of this grant proposal we will continue to add options to the code for different physics models. We have been working with two theorists (S. Jeschonnek and J-M. Laget) to acquire versions of their codes that include the fifth structure function f'_{LT} and will incorporate them into the program. A CLAS Note (2005-022) describing the project was published in fall, 2005 [7]. We will also develop and maintain the Richmond computing cluster for use by CLAS Collaboration members (see Section 2.1.4 for more details), and to help maintain online RECSIS, one of the CLAS data-acquisition monitoring tools. This will be in addition to normal collaboration duties (taking shifts, reviewing papers and analyzes, *etc.*). Finally, Gilfoyle has been elected chair of the Nuclear Physics Working Group. His tenure as chair of Physics at Richmond ended in May, 2006.

2.3 Education of Students

2.3.1 Undergraduate Research at the University of Richmond

Undergraduates have been involved in all the stages of the physics program described in this renewal application and the funds requested here 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 UC Santa Barbara, Virginia, North Carolina, Virginia Tech, Princeton, and Stanford. Five students from our laboratory have received doctorates. Three are currently staff scientists at NASA-Goddard, NASA-Huntsville, and the Jet Propulsion Laboratory (JPL), one is a faculty member at Stanford, and one is a post-doctoral fellow at Cornell in biological physics.

The students who work in our laboratory use modern computational techniques to 'mine' large data sets for information using our supercomputing cluster. They use the same instrument to perform sophisticated simulations of JLab experiments. They travel to JLab to take shifts and attend CLAS Collaboration meetings. Almost all of our students present their work at local, national, and international conferences [11, 12, 13, 14, 15, 16, 17, 18, 19]. The continued funding of this program will enable us to provide meaningful research experiences for many more undergraduate students.

2.3.2 High School Research Fellow

We request funding in this proposal to support an outreach program to create a research experience for a high-school science teacher. This High School Research Fellow (HSRF) would join our nuclear physics group for eight weeks during the first year and focus exclusively on research. They would repeat the experience in the following summer and begin work on a curricular project. The third year would follow the same pattern as the second year. We are applying the lessons learned in the National Science Foundation's Research Experience for Teachers (RET) program [74].

This program will enhance the productivity of our nuclear physics group. We will get a more mature, technically sophisticated colleague who is better equipped for research than many undergraduates and will work with us over several summers [75]. Researchers are simply more productive after their first summer.

This program supports the goals of the Department of Energy to 'greatly enhance their (the teachers) content knowledge and skills of mathematics and science' [76]. Programs like this one return teachers to the classroom with renewed enthusiasm and technical skills and the multi-year duration reinforces the gains made in the first summer so the effects are longer lasting [75]. The participants become better science teachers and can reach more young people. The impact of this program on the HSRF's teaching will be assessed with an array of pedagogical tools and the results will be disseminated via the web, conferences, and the existing network of RET alumni [74].

2.4 Institutional Support and Resources

2.4.1 Facilities and Support for Nuclear Physics

Our nuclear physics group at the University of Richmond is supported by a computing cluster developed in 2001 with NSF and University funds obtained by Gilfoyle and a former Richmond faculty member (M.F. Vineyard now at Union College). This cluster is for the exclusive use of our nuclear physics group though we support other Collaboration members who need it. The cluster is, in turn, supported by an array of computers for software development and non-CPU-intensive calculations and analysis. The system consists of 53, dual-processor machines running the Linux operating system and 3 TByte of RAID storage. Each machine has 18 GByte of disk space and 256 MByte of memory. The entire system resides on its own subnet and another machine acts as a firewall. It is in a laboratory designed for its needs with a 5-ton, 60,000-BTU air conditioner to cool the room, an upgraded electrical panel, and backup power. The support computers are located in an adjacent room. The entire facility is in the Physics Department research area.

The University supports our research efforts. One member of the University's Information Services is a Linux expert and he devotes half of his time to academic projects including support for the supercomputing cluster. He is responsible for keeping the CLAS software up-to-date, updating the Linux software on the cluster and in our laboratory, and general troubleshooting. The University also supports some undergraduate summer stipends for research. We have taken advantage of those in the past to hire additional students and will continue to apply for those in the future. The University supports student travel through competitive travel grants for most travel costs. In the last two years our group has received several thousand dollars in travel support from the University. The University also supports routine faculty travel to JLab.

2.4.2 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 at JLab. Gilfoyle spends about 1 day each week at JLab in addition to time spent on shift, at Collaboration meetings, *etc.* This proximity enables us to take students on shift with us and to attend Collaboration meetings and other events for little cost. As stated above the University supports routine faculty travel to JLab.

2.4.3 Sabbatical Leave

The PI (Gilfoyle) will be on sabbatical leave during the third year of this proposal (2009-2010).

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4 Publications Since Last Review

1. G.P. Gilfoyle, 'Out-of-Plane Measurements of the Fifth Structure Function of the Deuteron', Bull. Am. Phys. Soc., Fall DNP Meeting, DF.00010 (2006).

2. G.P. Gilfoyle and A. Afanasev, 'Radiative Corrections for Deuteron Electro-disintegration,' CLAS-Note 2005-022.

3. R.Burrell, K.Gill, and G.P.Gilfoyle, 'CLAS Simulations for $D(\vec{e}, e'p)n$,' Bull. Am. Phys. Soc., Fall DNP Meeting, 3A.00012 (2006).

4. K.Greenholt and G.P.Gilfoyle, 'Hadron Fiducial Cuts for the CLAS E5 Data,' Bull. Am. Phys. Soc., Fall DNP Meeting, 3A.00030 (2006).

5. R.Burrell and G.P.Gilfoyle, 'Momentum Corrections for the CLAS E5 Data Set,' University of Richmond Symposium, April 21, 2006.

6. K.Greenholt and G.P.Gilfoyle, 'Fiducial Cuts on CLAS for the E5 Data Set,' Bull. Am. Phys. Soc., Fall DNP Meeting, FR.0006(2005).

7. R.Burrell and G.P.Gilfoyle, 'Momentum Corrections for the E5 Data Set,' Bull. Am. Phys. Soc., Fall DNP Meeting, FR.00068(2005).

8. K.Greenholt and G.P.Gilfoyle, 'Generating Fiducial Cuts for CLAS E5,' University of Richmond Symposium, April 14, 2005.

9. R.Burrell and G.P.Gilfoyle, 'Momentum Corrections for the CLAS E5 Data Set,' University of Richmond Symposium, April 14, 2005.

10. K.Greenholt and G.P.Gilfoyle, 'Generating Fiducial Cuts for CLAS E5,' Bull. Am. Phys. Soc., April Meeting, S.06(2005).

11. R.Burrell and G.P.Gilfoyle, 'Momentum Corrections for the CLAS E5 Data Set,' Bull. Am. Phys. Soc., April Meeting, S.07(2005).

12. R. De Vita, M. Battaglieri, V. Kubarovski, *et al.* (The CLAS Collaboration), 'Search for the Theta+ pentaquark in the reactions $\gamma p \rightarrow \overline{K}_0 K^+ n$ and $\gamma p \rightarrow \overline{K}_0 K_0 p$', Phys. Rev. D **74**, 032001 (2006).

13. K.V. Dharmawardane, P. Bosted, S.E. Kuhn, Y. Prok, *et al.* (The CLAS Collaboration), 'Measurement of the x- and Q^2-dependence of the spin asymmetry A1 of the nucleon', Phys. Lett. B **641**, 11 (2006).

14. S. Chen, H. Avakian, V. Burkert, P. Eugenio, *et al.* (The CLAS Collaboration), 'Measurement of Deeply Virtual Compton Scattering with a Polarized Proton Target', Phys. Rev. Lett. **97**, 072002 (2006).

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16. B. McKinnon, K. Hicks, *et al.* (The CLAS Collaboration), 'Search for the Theta+ pentaquark in the reaction $\gamma d \rightarrow p K^- K^+ n$', Phys. Rev. Lett. **96**, 212001 (2006).

17. H. Egiyan, V. Burkert, *et al.* (The CLAS Collaboration), 'Single π^+ electroproduction on the proton in the first and second resonance regions at 0.25 GeV^2 < Q^2 < 0.65 GeV^2 using CLAS', Phys. Rev. C **73**, 025204 (2006).

18. R. Bradford, R. Schumacher, *et al.* (The CLAS Collaboration), 'Differential cross sections for $\gamma + p \to K^+ + Y$ for Λ and Σ_0 hyperons', Phys. Rev. C **73**, 035202 (2006).

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21. K. Egiyan, *et al.* (The CLAS Collaboration), 'Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei', Phys. Rev. Lett. **96**, 082501 (2006).

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23. S. Strauch, B. Berman, *et al.* (The CLAS Collaboration), 'Beam-Helicity Asymmetries in Double-Charged-Pion Photoproduction on the Proton', Phys. Rev. Lett. **95**, 162003 (2005).

24. K. Joo, L.C. Smith, *et al.* (The CLAS Collaboration), 'Measurement of the polarized structure function $\sigma_{LT'}$ for pion electroproduction in the Roper-resonance region', Phys. Rev. C **72**, 058202 (2005).

25. L. Morand, M. Garon, *et al.* (The CLAS Collaboration), 'Deeply virtual and exclusive electroproduction of ω-mesons', EPJA **24**, 445 (2005).

26. S. Taylor, G. Mutchler, *et al.* (The CLAS Collaboration), 'Radiative decays of the $\Sigma_0(1385)$ and $\Lambda(1520)$ hyperons', Phys. Rev. C **71**, 054609 (2005).

27. J. Price, *et al.* (The CLAS Collaboration), 'Exclusive photoproduction of the cascade (Xi) hyperons', Phys. Rev. C **71**, 058201 (2005).

28. L. Morand, *et al.* (The CLAS Collaboration), 'Deeply virtual and exclusive electroproduction of omega mesons', European Physics Journal, A 24, 445 (2005).

29. S. Taylor and G. Mutchler, *et al.* (The CLAS Collaboration), 'Radiative decays of the Σ^0(1385) and Λ (1520) hyperons', Physical Review, C71, 054609 (2005).

30. K.Greenholt and G.P.Gilfoyle, 'Generating Fiducial Cuts for CLAS E5', Bull. Am. Phys. Soc., April Meeting, S.06(2005).

31. R.Burrell and G.P.Gilfoyle, 'Momentum Corrections for the CLAS E5 Data Set', Bull. Am. Phys. Soc., April Meeting, S.07(2005).

32. J.Price, *et al.* (The CLAS Collaboration), 'Exclusive Photoproduction of the Cascade (Xi) Hyperons' Physical Review C **71**, 058201 (2005).

33. S. Niccolai, *et al.* (The CLAS Collaboration), 'Complete measurement of three-body photodisintegration of ^{3}He for photon energies between 0.35 and 1.55 GeV', Physical Review C **70**, 064003 (2004).

34. K. Joo, *et al.* (The CLAS Collaboration), 'Measurement of the Polarized Structure Function sigma(LT') for p(e(vec),e'pi+)n in the Delta resonance region', Physical Review C **70**, 042201R (2004).

35. C. Hadjidakis, M. Guidal, *et al.* (The CLAS Collaboration), 'Exclusive ρ_0 meson electroproduction from hydrogen at CLAS', Physics Letters B **605**, 256 (2005).

36. D. Protopopescu, *et al.* (The CLAS Collaboration), 'Survey of A'_{LT} asymmetries in semi-exclusive electron scattering on He4 and C12', Nuclear Physics A **748**, 357 (2005).

37. A.V. Stavinsky, K.R. Mikhailov, R. Lednicky, A.V. Vlassov, *et al.* (The CLAS Collaboration), 'Proton source size measurements in the $eA \to e'ppX$ reaction', Physical Review Letters, **93** (2004) 192301.

38. M. Mirazita, *et al.* (The CLAS Collaboration), 'Complete Angular Distribution Measurements of Two-Body Deuteron Photodisintegration between 0.5 and 3 GeV', Physical Review C **70** (2004) 014005.

39. P. Rossi, *et al.* (The CLAS Collaboration), 'Onset of asymptotic scaling in deuteron photodisintegration', Physical Review Letters, **94** (2005) 012301.

40. K. McCormick, *et al.* (The CLAS Collaboration), 'Tensor Polarization of the phi meson Photoproduced at High t', Physical Review C **69**, 032203 (2004).

5 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.

`http://www.jlab.org/Hall-B/general/phonebook.html`

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	Bernhard Mecking
Lawrence Weinstein	Michael Vineyard	Andrei Afanasev
David Jenkins	Jeffrey Lachniet	Latifa Elouadrhiri
Sabine Jeschonnek	J.W. Van Orden	John Parmentola
Anthony Fainberg	Mark Ito	Eliot Wolin
Arne Freyberger	Ivan Oelrich	Eric Gerdes

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	D.P. Weygand
M. Williams	M.H. Wood	A. Yegneswaran	J. Yun
L. Zana	J. Zhang	B. Zhao	Z. Zhao

6 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

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

1990-present - US Department of Energy ($1,361,000).

2002-2003 - SURA Sabbatical Support ($10,000).

2002-2003 - Jefferson Laboratory Sabbatical Support ($28,335).

2001-2002 - National Science Foundation ($175,000).

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).

1987-2002 - University of Richmond Research Grants($13,082).

Selected Service

2006 - present - Chair, Nuclear Physics Working Group, CLAS Collaboration.

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.

1997 - Chair, Jefferson Laboratory CLAS Collaboration nominating committee.

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.

Phi Beta Kappa, 1978.

Selected Listing of Refereed Publications

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

2. P. Rossi, *et al.*, (The CLAS Collaboration), 'Onset of asymptotic scaling in deuteron photodisintegration', Physical Review Letters, 94 012301 (2005).

3. D. Protopopescu, *et al.*, (The CLAS Collaboration), 'Survey of A'_{LT} asymmetries in semi-exclusive electron scattering on ^{4}He and ^{12}C', Nuclear Physics, A748, 357 (2005).

4. S. Stepanyan, *et al.*, (The CLAS Collaboration), 'Observation of an Exotic $S = +1$ Baryon in Exclusive Photoproduction from the Deuteron', Physical Review Letters **91**, 252001 (2003).

5. K. Joo, *et al.*, (The CLAS Collaboration), 'Measurement of Polarized Structure Function σ'_{LT}) for $p(\vec{e}, e'p)\pi^0$ from single π^0 electroproduction in the Delta resonance region', Physical Review C, Rapid Communications, **68**, 032201 (2003).

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

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

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

9. 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. 'Nuclear Physics Working Group Report', plenary session CLAS Collaboration Meeting, Nov 4, 2006.

2. 'Measurements of the Fifth Structure Function of the Deuteron', CLAS Collaboration Meeting, March 3, 2006.

3. 'Picking Winners: Emerging Technologies for Countering Terrorism', colloquium presented at Virginia Commonwealth University, Richmond, Virginia, April 22, 2005.

4. 'Out-of-Plane Measurements of the Structure Functions of the Deuteron', plenary session of the CLAS Collaboration Meeting, November 13, 2003.

5. 'Maintenance and Upgrading of the Richmond Physics Supercomputing Cluster', V.Davda and G.P.Gilfoyle, Program and Abstracts for the Fall 2003 Meeting of the Division of Nuclear Physics of the American Physical Society, Tucson, AZ, Oct 30 - Nov 1, 2003.

6. 'Using Nuclear Materials to Prevent Nuclear Proliferation', colloquium presented at Thomas Jefferson National Accelerator Facility, Norfolk, VA, March 7, 2001.

7. 'A New Teaching Approach to Quantum Mechanical Tunneling', Presented at the Conference on Computational Physics 1998, September 2-5, 1998, Granada, Spain.

7 Student Tracking Information

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

8 Discussion of Budget

YEAR 1

A.1 PI's summer salary based on 2/9's of academic years salary or $11,000 whichever is smallest.

B.3 Two undergraduate students for 10 summer weeks. This rate is the same as the University stipends. Includes 8.5% for fringe benefits.

B.5 Stipend for local high school teacher for 8 weeks. This is the same amount used by a similar program at Jefferson Lab in Newport News, Va. The University's Human Resources division will cover any advertising costs. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. $1,000 - One trip for the High School Research Fellow to attend a meeting like the American Association of Physics Teachers or Division of Nuclear Physics of the APS and for travel to JLab.
2. $936 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at $0.39 per mile. Note: routine faculty travel of this sort is covered by the University.
3. $972 - Lodging at the JLab residence facility ($54/night) during shifts for faculty and students and Collaboration meetings based on 12-16 shifts/yr and three Collaboration meetings of about 3 days/meeting.

   Total = $2,908

F.1 - $2,563 - Computer parts and repair (*e.g.*, replace burned-out power supplies for the RAID in the computing cluster), office supplies, *etc* for our 54-node computing cluster and associated laboratory at Richmond and an office we have at JLab.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.

YEAR 2

A.1 PI's salary ($11,000 in first year) adjusted each year by 3% for inflation.

B.3 Two undergraduate students for 10 summer weeks and adjusted each year for 3% inflation. Includes 8.5% for fringe benefits.

B.5 Stipend for High School Research Fellow for 8 weeks and adjusted each year for 3% inflation. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. $1,030 - One trip for the High School Research Fellow to attend an annual meeting like the American Association of Physics Teachers or Division of Nuclear Physics of the APS and for travel to JLab (adjusted each year for 3% inflation).

2. \$964 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab at \$0.39 per mile (adjusted each year for 3% inflation). Note: routine faculty travel of this sort is covered by the University.
3. \$1001 - Lodging at the JLab residence facility (\$54/night) during shifts for faculty and students and Collaboration meetings based on 12-16 shifts/yr and three Collaboration meetings of about 3 days/meeting (adjusted each year for 3% inflation).

   Total = \$2,995

F.1 - \$2,160 - Computer parts and repair (*e.g.*, replace burned-out power supplies for the RAID in the computing cluster), office supplies, *etc* for our 54-node computing cluster and associated laboratory at Richmond and an office we have at JLab adjusted each year for 3% inflation.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.

YEAR 3

A.1 PI's salary (\$11,000) adjusted each year by 3% for inflation.

B.4 Two undergraduate students for 10 summer weeks and adjusted each year for 3% inflation. Includes 8.5% for fringe benefits.

B.2 Salary for High School Research Fellow for 8 weeks and adjusted each year for 3% inflation. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. \$1,061 - One trip for the High School Research Fellow to attend an annual meeting like the American Association of Physics Teachers or Division of Nuclear Physics of the APS and for travel to JLab (adjusted each year for 3% inflation).
2. \$993 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab at \$0.39 per mile (adjusted each year for 3% inflation). Note: routine faculty travel of this sort is covered by the University.
3. \$1,031 - Lodging at the JLab residence facility (\$54/night) during shifts for faculty and students and Collaboration meetings based on 16 shifts/yr and three Collaboration meetings of 3 days/meeting (adjusted each year for 3% inflation).

   Total = \$3,085

F.1 - \$2,725 - Computer parts and repair (*e.g.*, replace burned-out power supplies for the RAID in the computing cluster), office supplies, *etc* for our 54-node computing cluster and associated laboratory at Richmond and an office we have at JLab adjusted each year for 3% inflation.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.