# Continuation Progress Report

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# 1 Introduction

In this report we describe the progress made during the period February 13, 2007 to February 14, 2008 under contract number DE-FG02-96ER40980. See listing on page 5 for a summary. The experimental work described here is part of the electromagnetic nuclear physics program in Hall B at the Thomas Jefferson National Accelerator Facility (Jefferson Lab or JLab). The group includes a single faculty member (Gilfoyle) and 3-5 undergraduates (the University of Richmond is a primarily undergraduate institution). Gilfoyle is co-author on six refereed articles during this period [1, 2, 3, 4, 5, 6]. He is spokesperson on a CLAS Approved Analysis (*Out-of-Plane Measurements of Deuteron Structure Functions*) that was approved by the CLAS Collaboration in November, 2003 [7].[1] We are also part of the analysis effort for CLAS experiment E94-017 to measure the magnetic form factor of the neutron or $G_M^n$ (*The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Electron-Neutron to Electron-Proton Scattering in Deuterium*) which is under Collaboration review [8, 9].[2] Gilfoyle was spokesperson and contact person on a new proposal to measure $G_M^n$ using the same technique as part of the first five years of running after the 12-GeV Upgrade at JLab (*Measurement of the Neutron Magnetic Form Factor at High* $Q^2$ *Using the Ratio Method on Deuterium*, PR12-07-104). The JLab PAC approved the proposal in August, 2007 [10, 11].[3] Gilfoyle is also co-spokesperson on a JLab 12-GeV proposal entitled *Quark Propagation and Hadron Formation* that was approved by PAC30 [13, 14]. Gilfoyle was invited to give two technical talks on the $G_M^n$ analysis [15, 16]. The proceedings for Reference [16] have been published electronically [17]and the the proceedings for Reference [15] have been submitted. Gilfoyle was invited to give two others talks to undergraduates (at the fall DNP meeting) and to high school students [18, 19].

Last summer, two undergraduates (Kirill Dergachev and Justin Nguyen) worked in Gilfoyle's nuclear physics lab at the University of Richmond. One of these students presented his work at the Fall, 2007 meeting of the DNP [20]. Three other students, Kuri Gill, Kristen Greenholt, and Robert Burrell, who worked in our group over the past three years wrote their senior theses on that research. They all presented there work at APS meetings (a total of six separate presentations) before the previous budget period. Burrell and Gill are applying to graduate school in physics and computer science, respectively.

Service work performed by our group includes maintaining one of the CLAS online monitoring tools, radiative correction software, and access to a computing cluster at the University of Richmond used by several CLAS Collaborators. In the last year Gilfoyle has served the CLAS Collaboration as chair of the Nuclear Physics Working Group and as a member of the CLAS Coordinating Committee (the main governing body of the Collaboration). He has also served as chair of the CLAS12 reconstruction group and as a reviewer for an internal Collaboration review of the CLAS12 drift chamber design in March, 2007 [21, 22, 23].

We anticipate that we will have about $6,000 remaining in unexpended funds at the end of the current budget period. This is more than 10% of the funds available for the budget period and is the result of obtaining University of Richmond funds to support two undergraduates last summer in our laboratory so grant funds were not spent as expected. We will use these unexpended funds to support additional students in the future. As usual, undergraduates were involved in all aspects of our work. Richmond is a primarily undergraduate institution. Below, we discuss recent accomplishments, describe plans for the next budget period, and assess the impact of our work.

# 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 be calculated in the laboratory frame in terms of four elastic form factors (electric and magnetic ones for each nucleon) that characterize the distributions of charge and magnetization within the proton and neutron.

[1] A CLAS Collaboration member can write a proposal to analyze existing data which is reviewed by a committee of Collaboration members, and defended before the Collaboration who then vote to approve it.

[2] The CLAS Collaboration rules for publication require first a technical review of the analysis work by a committee of Collaboration members. After approval a draft of the paper for publication undergoes another review before the final paper is submitted to a journal.

[3] The DOE plans to upgrade the accelerator at JLab from a beam energy of 6 GeV to 12 GeV. The upgrade will require extensive changes to the accelerator and to CLAS to take advantage of the new physics opportunities. The JLab, 12-GeV-Upgrade is one of the highest priorities of the DOE office of Science in the next 20 years [12].

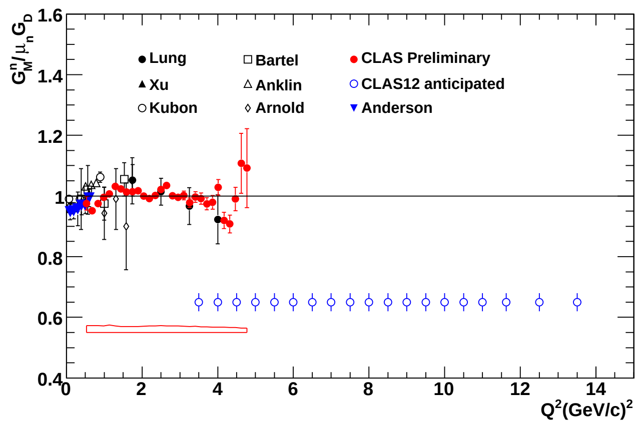


Figure 1: Preliminary results (red) for CLAS $G_M^n$ measurement and expected data range and uncertainties (blue) for the CLAS12 $G_M^n$ proposal.

We are part of a broad assault on the four elastic nucleon form factors at JLab [24]. Our focus is on $G_M^n$, the magnetic form factor of the neutron. To measure $G_M^n$ we use the ratio of elastic $e-n$ to elastic $e-p$ scattering on deuterium which is less vulnerable to uncertainties than previous methods [9]. We have completed data collection and most of the analysis for a measurement of $G_M^n$ made during the E5 running period in the range $\mathrm{Q}^2 = 0.2 - 5.0$ (GeV/c)$^2$ [8, 9, 17]. A report describing the analysis of two out of the three data sets from the E5 running period is near the end of its Collaboration review. Preliminary results can be seen in Figure 1 along with some of the world data for $G_M^n$. Our group at Richmond has taken on the analysis of the third data set. We have also submitted a proposal to the JLab Program Advisory Committee (PAC) to make the same measurements at higher $\mathrm{Q}^2$ as part of the JLab 12-GeV Upgrade. Figure 1 shows the anticipated data range and uncertainties. The proposal was approved by PAC32 in August 2007 (spokesperson and contact person: Gilfoyle) [10, 11]. In the next budget period we will continue the analysis of the remaining E5 data set to extract $G_M^n$. This last data set used a reversed field setting of the CLAS torus to reach lower $\mathrm{Q}^2$ which will overlap with existing measurements from other laboratories. The impact of the entire E5 data set and the extraction of $G_M^n$ will have significant impact on our knowledge of the distribution of charge and current within the neutron (see Figure 1) and on the extraction of GPDs.

# 3 Out-of-Plane Measurements of Deuteron Structure Functions

The hadronic model of nuclear physics has been successful at low $\mathrm{Q}^2$, but it is not well-developed in the GeV region where there are few measurements. We need a baseline for the hadronic model so deviations at higher $\mathrm{Q}^2$ can be attributed to quark-gluon effects with greater confidence [25, 26]. To this end, we are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e}, e'p)n$ with CLAS. The cross section is

$$\frac{d\sigma^5}{d\omega d\Omega_e d\Omega_{pq}} = C\left(\rho_l f_l + \rho_t f_t + \rho_{TT} f_{TT} \cos\phi_{pq} + \rho_{LT} f_{LT} \cos 2\phi_{pq} + h\rho'_{LT} f'_{LT} \sin\phi_{pq}\right) \tag{1}$$

where $C$ and the $\rho_i$ are functions of the known electron parameters, $h$ is the beam helicity, and $\phi_{pq}$ is the azimuthal angle between the scattering plane (defined by the incoming and outgoing electron 3-momenta) and the reaction plane (defined by the 3-momentum transfer and the ejected proton momentum) [7, 27]. The unique, nearly-$4\pi$ solid angle of CLAS creates an opportunity to extract the $\phi_{pq}$-dependent structure functions $f'_{LT}$, $f_{LT}$, and $f_{TT}$ in a model-independent way.

These structure functions are extracted using asymmetries that reduce our sensitivity to experimental effects. To study $f'_{LT}$ we use the asymmetry $A'_{LT} = \rho'_{LT} f'_{LT}/(\rho_L f_L + \rho_T f_T)$ which can be extracted using the $\sin\phi_{pq}$-weighted moments of the angular distributions measured with CLAS over the range $\mathrm{Q}^2 = 0.2 - 5.0$ (GeV/c)$^2$ [7, 27]. We are studying the reaction in quasi-elastic kinematics and our preliminary results for $A'_{LT}$ show significant structure which is reproduced by a recent calculation from Jeschonnek and van Orden and disagrees with others [28, 29, 30]. In the last budget period we have completed simulations of the reaction which show that our analysis approach is sound. We simulated a known asymmetry and found the our analysis code accurately reproduced the input. This work is part of a CLAS Approved Analysis (spokesperson: Gilfoyle). We note these data sets are the same ones used in the $G_M^n$ analysis described in Section 2. In the next budget period we will complete the analysis for the $A'_{LT}$ asymmetry including a measurement of the systematic uncertainty and a comparison of our results with a new calculation from Jeschonnek and van Orden. The work will be described in a CLAS Analysis Note and submitted for Collaboration review in preparation for final publication. The impact of this work will be test the hadronic model in an energy and $Q^2$ regime where data are scarce. By measuring $A'_{LT}$ we are shedding new light on a little-studied part of the $NN$ force.

# 4 Technical Projects

The measurements of the nuclear reactions described above are subject to radiative corrections. Gilfoyle has written a program for exclusive reactions with electrons [31] using a new method developed by Afanasev, *et al.* [32] and deuteron response functions calculated with the program DEEP [33]. We maintain a website to distribute the radiative correction code for the reaction $D(\vec{e}, e'p)n$ [34].

We are committed to development projects for the JLab 12-GeV Upgrade to double the beam energy of the electron accelerator and enhance the experimental equipment in Hall B [35]. We will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction. We have begun work on this project by developing event generator 'plug-ins' for the CLAS12 simulation code and optimizing the set up for the CLAS12 simulation for off-site users [20].

Gilfoyle was responsible for maintaining one of the CLAS online monitoring tools that does a full reconstruction of a subset of the data as it is collected, extracts features of the incoming data like number of tracks per event and updates a time series on the CLAS website. In fall, 2007, the data acquisition for CLAS was changed from Sun computers to linux machines which required extensive modifications especially to the Make scheme in order to get the monitoring software working again.

We also continue to maintain a computing cluster at the University of Richmond for our use and the work of several CLAS Collaborators.

In the next budget period we hope to find an undergraduate computer science and physics major who will build on the progress we made last summer [20]. The impact of this work will be to speed the design of the CLAS12 detector.

# 5 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable feature of QCD and understanding it is an essential goal of nuclear physics [26]. We propose to use the nucleus as a "detector"; measuring the ratio of hadrons produced on nuclear targets relative to deuterium to extract the lifetime of a deconfined quark after it is struck by a virtual photon. In addition, the kinematic dependence of the transverse momentum broadening will enable us to measure the time interval required to form the hadronic color field around the struck quark. A proposal to do this experiment at high $Q^2$ as part of the 12-GeV Upgrade was approved by the JLab PAC in August, 2006 [13, 14]. Gilfoyle is a co-spokesperson on that proposal and will be responsible for analyzing the $\pi^0$, $\eta$, and $\eta'$ production. In the last budget period, we developed code to extract the production length (the distance covered by the deconfined quark before it is neutralized by an anti-quark). In the next budget period we will be focused primarily on the projects in Sections 2-4.

# 6 CLAS Collaboration Service Work

Gilfoyle served as chair of the Nuclear Physics Working Group during the last budget period. He was responsible for managing technical reviews and presentations, organizing meetings, and keeping the rest of the CLAS Collaboration informed of the activities of the working group. He is also a member of the CLAS12 Software Group and chaired the reconstruction group [21, 22]. He was also co-author of an internal Collaboration review team that examined the CLAS12 drift chamber design and plans. This review was done to prepare for a major external review of the design of the CLAS12 drift chambers as part of the work to achieve Critical Design Decision - 2 (CD2) [23].

# Summary of Contract-Related Activities

Refereed Publications

1. H. Denizli, S. Dytman, J. Mueller, *et al.* (The CLAS Collaboration), '$Q^2$ Dependence of the $S_{11}(1535)$ Photocoupling and Evidence for a P-wave resonance in eta electroproduction', Phys. Rev. C **76**, 015204 (2007).
2. I. Hleiqawi, K. Hicks, D. Carman, T. Mibe, G. Niculescu, A. Tkabladze, *et al.* (The CLAS Collaboration), 'Cross sections for the gamma p -¿ K*0 Sigma+ Reaction at E(gamma) = 1.7 - 3.0 GeV', Phys. Rev. C **75**, 042201 (2007).
3. 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 $Q^2$', Phys. Rev. Lett. **98**, 262502 (2007).
4. R. Bradford, R. Schumacher, *et al.* (The CLAS Collaboration), 'First Measurement of Beam-Recoil Observables Cx and Cz in Hyperon Photoproduction', Phys. Rev. C **75**, 035205 (2007).
5. P. Ambrozewicz, D.S. Carman, R. Feuerbach, M.D. Mestayer, B.A. Raue, R. Schumacher, A. Tkabladze, *et al.* (The CLAS Collaboration), 'Separated Structure Functions for the Exclusive Electroproduction of K+Lambda and K+Sigma0 Final States', Phys. Rev. C **75**, 045203 (2007).
6. P.E. Bosted, K.V.Dharmawardane, G.E. Dodge, T.A. Forest, S.E. Kuhn, Y. Prok, *et al.* (The CLAS Collaboration), 'Quark-Hadron Duality in Spin Structure Functions g1p and g1d', Phys. Rev. C **75**, 035203 (2007).

New Proposals

1. "Measurement of the Neutron Magnetic Form Factor at High $Q^2$ Using the Ratio Method in Deuterium", G.P. Gilfoyle$^{*\dagger}$, W.K.Brooks$^*$, M.F. Vineyard$^*$, J.D. Lachniet$^*$, S.E. Kuhn, L.B.Weinstein, K. Hafidi$^*$, M. Holtrop, M. Garcon, Jefferson Lab Experiment PR12-07-104 (2007).

Invited Talks

1. G.P. Gilfoyle, 'High-Precision Measurement of GMn with CLAS', Workshop on Exclusive Reactions at High Momentum Transfer, Newport News, Virginia, May 22, 2007.
2. G.P. Gilfoyle, 'Measuring Form Factors and Structure Functions with CLAS', HEPMAD07, Antananarivo, Madagascar, September 11, 2007.
3. G.P. Gilfoyle, 'Nuclear Physics at the University of Richmond', American School of Antananarivo, Antananarivo, Madagascar, September 13, 2007.
4. G.P. Gilfoyle, 'Hunting for Quarks', Conference Experience for Undergraduates (CEU) Nuclear Physics Seminar, Fall, 2007 meeting of the Division of Nuclear Physics of the APS, October 13, 2007.

Contributed talks

1. K.Dergachev and G.P.Gilfoyle, 'CLAS12 Simulation Installation and Optimization', Bull. Am. Phys. Soc., Fall DNP Meeting, DA.00019(2007).

Service Work

1. L.B.Weinstein, G.P.Gilfoyle, F.J.Klein, 'Charged Particle Tracking in CLAS12', report of the internal CLAS Collaboration review committee, Feb., 2007.
2. Chair, Nuclear Physics Working Group and member of the CLAS Coordinating Committee.

$^*$- spokesperson, $^\dagger$ - contact person.

# References


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[9] J.D. Lachniet, "A High Precision Measurement of the Neutron Magnetic Form Factor Using the CLAS Detector", thesis, Carnegie Mellon University.

[10] "Measurement of the Neutron Magnetic Form Factor at High Q$^2$ Using the Ratio Method in Deuterium", G.P. Gilfoyle, W.K.Brooks, M.F. Vineyard, J.D. Lachniet, S.E. Kuhn, L.B.Weinstein, K. Hafidi, M. Holtrop, M. Garcon, Jefferson Lab Experiment PR-12-07-104 (2007).

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[13] "Quark Propagation and Hadron Formation", K. Hafidi, J.Arrington, L. El Fassi, D.F. Geesaman, R.J. Holt, B. Mustapha, D.H. Potterveld, P.E.Reimer, P. Solvignon, K. Joo, M. Ungaro, G. Niculescu, I. Niculescu, W.K. Brooks, M. Holtrop, K. Hicks, T. Mibe, L.B. Weinstein, M. Wood, G.P. Gilfoyle, H. Hakobyan, Jefferson Lab Experiment PR-12-06-117 (2006).

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[21] G.P. Gilfoyle, 'Software Report', plenary session, Hall-B, 12-GeV Upgrade Workshop, May 15, 2007.

[22] G.P. Gilfoyle, 'CLAS12 Reconstruction Overview', Hall-B, 12-GeV Upgrade Workshop, May 14, 2007.

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