Continuation Progress Report

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PI: Gerard P. Gilfoyle

Department of Physics, University of Richmond, 28 Westhampton Way,
Richmond, VA 23173

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Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period February 13, 2009 to February 14, 2010 under contract number DE-FG02-96ER40980. See listing on pages 5-6 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 (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 twelve refereed articles during this period [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. He is spokesperson on a CLAS Approved Analysis *Out-of-Plane Measurements of Deuteron Structure Functions* [13].[1] We are part of the analysis effort for CLAS experiment E94-017 to measure the magnetic form factor of the neutron or G_M^n [14]. The results for two out of three sets of run conditions have been published [2] and we continue work on the third set. Gilfoyle is spokesperson and contact person on a new experiment 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 [15] (approved by PAC32).[2] The experiment was assigned a scientific rating of A^- by PAC35 in January, 2010 and 30 days of beamtime were allocated for it [17]. Gilfoyle is also co-spokesperson on a JLab 12-GeV proposal entitled *Quark Propagation and Hadron Formation* that was approved by PAC30 [18, 19]. In the last year Gilfoyle was invited to give one technical talk on the G_M^n analysis [20] and one public lecture on the physics program at JLab [21]. He presented a contributed talk on the published G_M^n results at the fall DNP meeting [22]. Last summer, four undergraduates (Calina Copos, Matt Jordan, Matt King, and Mark Moog) worked in Gilfoyle's nuclear physics lab at the University of Richmond. Three of them presented their work at the Fall, 2009 meeting of the DNP [23, 24, 25]. Gilfoyle is on sabbatical during the 2009-2010 academic year at JLab.

Service work performed by the group includes maintaining one of the CLAS online monitoring tools and radiative correction software. Gilfoyle continues to serve as chair of the CLAS Collaboration's Nuclear Physics Working Group and as a member of the CLAS Coordinating Committee (the main governing body of the Collaboration). He also served as a reviewer for the National Science Foundation.

We anticipate there will be about $8,000 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 fewer grant funds were spent. We were also able to obtain support for conference travel from the University of Richmond (for Gilfoyle and three undergraduates) and for travel to JLab from JSA/SURA as part of Gilfoyle's sabbatical. We will use these unexpended funds to support additional students and travel 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 and describe plans for the next budget period.

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.

We are part of a broad assault on the four elastic nucleon form factors at JLab. Our focus is on G_M^n, the magnetic form factor of the neutron. To measure G_M^n we use the ratio of quasielastic (QE) $e-n$ to $e-p$ scattering on deuterium which is less vulnerable to uncertainties than previous methods [26]. In the last year we have published our results for two of three sets of running conditions for G_M^n collected with the CLAS detector at JLab in the range $Q^2 = 1.0 - 4.8$ $(GeV/c)^2$ [2]. These results can be seen as the red, open circles in the figure. Our group at Richmond has taken on the analysis of the third data set. This last data set used a reversed field setting of the CLAS torus to reach lower Q^2 which will overlap with existing measurements from other laboratories. We have moved the data-summary files to the cluster at Richmond

[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 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 Upgrade is one of the highest priorities of the DOE office of Science in the next 20 years [16].

and made some preliminary studies to check the consistency with previous work in Ref. [26]. In the next budget period analysis of these data will begin in earnest.

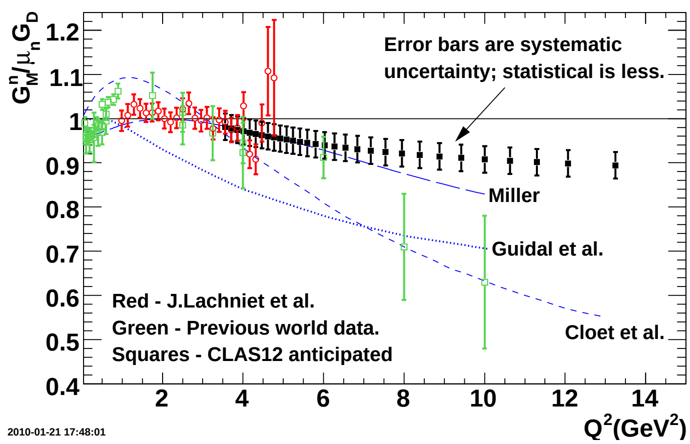

Figure 1: Results (red) for CLAS G_M^n measurement and other world data (green) and expected data range and uncertainties (black) for the CLAS12 G_M^n proposal. Curves and references are in Ref. [17].

Gilfoyle is spokesperson and contact person for experiment E12-07-104 to extend these measurements of G_M^n to higher Q^2 after the completion of the 12 GeV Upgrade at JLab [15, 27]. The figure shows the anticipated data range, binning, and systematic uncertainties. The proposal was reviewed again by PAC35 to assign scientific priority and allocate beamtime. To prepare for that update we simulated our capability to reduce inelastic backgrounds in the highest Q^2 bin where the background will be worse. By taking advantage of the unique, large solid-angle of CLAS12, we were able to reduce the anticipated background contribution to the QE events from 40% down to 11%. The experiment received a rating of A$^-$ from PAC35 and 30 days of beamtime were allocated. In the next budget period we will continue the analysis of the remaining E5 data set to extract G_M^n. The impact of the entire E5 data set and the extraction of G_M^n will have significant impact on our knowledge of the neutron and nucleon structure.

3 Out-of-Plane Measurements of Deuteron Structure Functions

The hadronic model of nuclear physics has been successful at low 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 Q^2 can be attributed to quark-gluon effects with greater confidence [28, 29]. 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 [13]. 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 ρ_i are functions of the known electron parameters, h is the beam helicity, and ϕ_{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) [13, 30]. The unique, nearly-4π solid angle of CLAS creates an opportunity to extract the ϕ_{pq}-dependent structure function f'_{LT} in a model-independent way.

The structure function is extracted using an asymmetry that reduces our sensitivity to experimental effects. To study f'_{LT} we use $A'_{LT} = \rho'_{LT} f'_{LT}/(\rho_L f_L + \rho_T f_T)$ as a function of the missing momentum $\vec{p}_m = \vec{q} - \vec{p}_p$ where $\vec{q}$ is the 3-momentum transfer and $\vec{p}_p$ is the measured proton momentum. This asymmetry can be extracted using the $\sin\phi_{pq}$-weighted moments of the angular distributions measured with CLAS over the range $Q^2 = 0.2 - 5.0\ (\mathrm{GeV/c})^2$ [13, 30]. 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 [31, 32, 33]. 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 used different algorithms to simulate both the low and high p_m regions to obtain adequate statistics from the Monte Carlo calculation[23]. Our previous simulations were restricted to low missing momentum. We have also completed a study of the systematic uncertainties on A'_{LT} which range from 0.0008-0.017 and are significantly less than the statistical uncertainties across the full range of missing momentum [24]. 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 of A'_{LT} and begin the Collaboration review. This work will test the hadronic model in an energy and Q^2 regime where data are scarce and shed new light on a little-studied part of the NN force.

4 Technical Projects

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 [34]. We will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction in the new Hall-B detector CLAS12. In the last year we have investigated the CLAS12 neutron detection efficiency in the TOF system using the programs gemc (for simulation) and Socrat (reconstruction and analysis) [25]. Neutron events were simulated with gemc and Socrat was modified to include neutral hits from the TOF system in the datastream. The CLAS12 TOF system will have three layers of scintillators including one layer that will be reused from the current CLAS detector (CLAS6). We studied this to-be-reused layer because we can compare its efficiency with the efficiency we measured in CLAS6 as part of the analysis of the G_M^n experiment described above. Our results were consistent with the measured neutron efficiency in CLAS6. We have also implemented part of the CLAS12, forward-detector, electromagnetic calorimeter system in gemc. This CLAS12 system will consist of a new pre-shower calorimeter placed in front of the reused CLAS6 electromagnetic calorimeter (EC). The EC geometry was added as a Geant4 generalized trapezoid and the data from the EC included in the output banks of gemc. The early results show the expected behavior for the energy deposited in the EC. In the next year we expect to reconstruct the EC neutral events in Socrat, add the pre-shower calorimeter to the EC system, and study the neutron efficiency of this detector. Again we will compare the EC efficiency with the CLAS6 results measured during the G_M^n experiment.

We also continue to maintain a computing cluster at the University of Richmond for our use and the work of several CLAS Collaborators. We have recently received a grant from NSF ($162,000) to replace our existing, ageing cluster. In the next year we will purchase and install the new cluster and will use it to study distributed computing for the CLAS12 data analysis.

Gilfoyle maintains a program for calculating radiative corrections for the exclusive reaction $D(e,e'p)n$ [35] using a method developed by Afanasev, *et al.* [36] and deuteron response functions calculated with the program DEEP [37]. A website is used to distribute the radiative correction code [38].

Gilfoyle is 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.

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 [29]. 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. 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. This experiment (E12-06-117) is part of the 12-GeV Upgrade was approved by PAC30 [18, 19]. Gilfoyle is a co-spokesperson on that proposal and will be responsible for analyzing the π^0, η, and η' production. In the next budget period we will be focused primarily on the projects described above.

6 CLAS Collaboration Service Work

Gilfoyle continued to serve 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. In the next year, he will organize a CLAS12 software workshop at the University of Richmond using funding from JSA/SURA and the University of Richmond.

Summary of Contract-Related Activities

Refereed Publications

1. M. Nozar et al. Search for the photo-excitation of exotic mesons in the $pi^+\pi^+\pi^-$ system. *Phys. Rev. Lett.*, 102:102002, 2009.
2. J. Lachniet, A. Afanasev, H. Arenhövel, W. K. Brooks, G. P. Gilfoyle, D. Higinbotham, S. Jeschonnek, B. Quinn, M. F. Vineyard, et al. Precise Measurement of the Neutron Magnetic Form Factor G_M^n in the Few-GeV^2 Region. *Phys. Rev. Lett.*, 102(19):192001, 2009.
3. M. Battaglieri et al. Measurement of direct $f(980)$ photoproduction on the proton. *Phys. Rev. Lett.*, 102(10):102001, Mar 2009.
4. M. Dugger et al. π^+ photoproduction on the proton for photon energies from 0.725 to 2.875 gev. *Phys. Rev. C*, 79(6):065206, Jun 2009.
5. W. Chen et al. Measurement of the differential cross section for the reaction $\gamma n \rightarrow \pi - p$ from deuterium. *Phys. Rev. Lett.*, 103(1):012301, Jul 2009.
6. R. Nasseripour et al. Photodisintegration of $\mathrm{He}-4$ into $p+t$. *Phys. Rev. C*, 80(4):044603, Oct 2009.
7. X. Qian et al. The extraction of ϕN total cross section from $d(\gamma, pK^+K^-)n$. *Phy. Lett. B*, 680(5):417, Oct 2009.
8. M. Battaglieri et al. Photoproduction of $\pi^+\pi^-$ meson pairs on the proton. *Phys. Rev. D*, 80(7):072005, Oct 2009.
9. M. Williams et al. Partial wave analysis of the reaction $\gamma p \rightarrow p\omega$ and the search for nucleon resonances. *Phys. Rev. C*, 80(6):065209, Dec 2009.
10. M. Williams et al. Differential cross sections and spin density matrix elements for the reaction $\gamma p \rightarrow p\omega$. *Phys. Rev. C*, 80(6):065208, Dec 2009.
11. M. Williams et al. Differential cross sections for the reactions $\gamma p \rightarrow p\eta$ and $\gamma p \rightarrow p\eta'$. *Phys. Rev. C*, 80(4):045213, Oct 2009.
12. I. G. Aznauryan et al. Electroexcitation of nucleon resonances from CLAS data on single pion electroproduction. *Phys. Rev. C*, 80(5):055203, Nov 2009.

New Proposals, Updates, and Letters-of-Intent.

1. 'Update for E12-07-104: Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on Deuterium', G.P.Gilfoyle*† *et al.* Jefferson Lab Experiment E12-07-104, A^- scientific rating, approved for 30 days.
2. 'The EMC Effect in Spin Structure Functions', W.K. Brooks*† *et al.*, Jefferson Lab Experiment LOI-10-005, approved.
3. 'Nuclear Exclusive and Semi-inclusive Physics with a New CLAS12 Low Energy Recoil Detector', K. Hafidi*† *et al.*, Jefferson Lab Experiment LOI-10-009, approved.
4. 'Precision Measurement of the Neutron Magnetic Form Factor at $Q^2 = 16.0$ and 18.0 (GeV/c)^2 by the Ratio Method', B. Wojtsekhowski*† *et al.*, Jefferson Lab Experiment PR-10-005, deferred.

Invited Talks

1. G.P. Gilfoyle, 'Nuclear Physics and National Security', Franklin and Marshall College, April 6, 2009.
2. G.P. Gilfoyle, 'Precise Measurement of the Neutron Magnetic Form Factor', Argonne National Laboratory, June 1, 2009.

3. G.P. Gilfoyle, ‘What’s Inside the Nucleus?’, University of Richmond, April 16, 2009.

4. G.P. Gilfoyle, ‘Nuclear Physics and National Security in an Age of Terrorism’, University of Richmond, April 15, 2009.

Contributed talks and posters.

1. G.P.Gilfoyle, ‘Precise Measurement of the Neutron Magnetic Form Factor in the Few-GeV2 Region’, Bull. Am. Phys. Soc., Fall DNP Meeting, BF.00008 (2009), talk.

2. C.Copos and G.P.Gilfoyle, ‘Testing Analysis Algorithms for the $^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$ Reaction’, Bull. Am. Phys. Soc., Fall DNP Meeting, GB.00059 (2009), poster.

3. M.Jordan and G.P.Gilfoyle, ‘Systematic Uncertainties of Out-of-Plane Measurements of the Fifth Structure Function of the Deuteron’, Bull. Am. Phys. Soc., Fall DNP Meeting, GB.00059 (2009), poster.

4. M.Moog and G.P.Gilfoyle, ‘Simulating the Neutron Detection of the CLAS12 Detector’, Bull. Am. Phys. Soc., Fall DNP Meeting, GB.00086 (2009), poster.

Service Work

1. Chair, Nuclear Physics Working Group and member of the CLAS Coordinating Committee.

2. Reviewer, National Science Foundation, Nuclear Physics Program, Office of Physics.

*- spokesperson, † - contact person.

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