Continuation Progress Report

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Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period February 13, 2010 to February 14, 2011 under contract number DE-FG02-96ER40980 entitled *Nuclear and Particle Physics at the University of Richmond*, Gerard P Gilfoyle (PI). [1] See 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 nine refereed articles during this period [1, 2, 3, 4, 5, 6, 7, 8, 9]. He is spokesperson on a CLAS Approved Analysis *Out-of-Plane Measurements of Deuteron Structure Functions* [10].[2] 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 [11]. The results for two out of three sets of run conditions have been published [12] and we continue work on the third set. Gilfoyle is spokesperson and contact person on a new experiment to measure G_M^n entitled *Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on Deuterium* using the same technique that will run in the first five years after the 12 GeV Upgrade at JLab [13] (approved by PAC32) [14].[3] The experiment was assigned a scientific rating of A^- by PAC35 in January, 2010 and 30 days of beamtime were allocated [15, 16]. Gilfoyle is also co-spokesperson on a JLab 12-GeV proposal entitled *Quark Propagation and Hadron Formation* that was approved by PAC30 [17, 18]. In the last year Gilfoyle was invited to give technical talks on the G_M^n analysis [19], the prospects for measuring Bose-Einstein Correlations at the Electron-Ion Collider [20], and the few-body physics program at CLAS [21], and two public lectures on the physics and science policy [22, 23]. Last summer, three undergraduates (Josh Carbonneau, Chris Musalo, and Mark Moog) and one high school student (Keegan Sherman) worked in Gilfoyle's nuclear physics lab at the University of Richmond. Another student (Stacey Barker) was supported by the grant and worked with Dennis Weygand (JLab staff member) and Gilfoyle at JLab. Two of these undergraduates were supported by the grant and two were supported by other University of Richmond funds. The three University of Richmond undergraduates lab presented their work at the Fall, 2010 meeting of the DNP [24, 25, 26]. Our laboratory at the Richmond was enhanced with the development of a new computing cluster obtained with grant funds from the National Science Foundation Major Research Instrumentation program. Gilfoyle was 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, radiative correction software, and the new computing cluster. Gilfoyle was chair of the organizing committee of the CLAS12 Software Workshop that was held at Richmond on May 25-26, 2010. He has completed his term 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 served as a reviewer for the National Science Foundation, DOE, and for the CLAS Collaboration.

We anticipate there will be about $12,000 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 undergraduates. We were also able to obtain support for conference travel from the University of Richmond and the American Physical Society (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. Below, we discuss recent accomplishments and describe plans for the next budget period.

2 Physics Projects

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)

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[2] 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.

[3] The DOE is now doubling the accelerator energy at JLab from 6 GeV to 12 GeV. A new detector in Hall B is under construction to take advantage of the new physics opportunities.

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 and our focus is on G_M^n, the magnetic form factor of the neutron (Experiment E94-017). Experiment E95-017 consists of three data sets with different running conditions. The analysis of the first two data sets has been published and we have begun work on the third [12]. We have had limited personnel to work on this analysis in the last budget period because of the focus on other projects discussed below. As those projects near completion in the next budget period analysis of these data will begin in earnest.

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 [13, 14]. The proposal has a scientific rating of A^- and 30 days of beamtime have been allocated [16]. In the next budget period we will continue the analysis of the remaining E5 data set to extract G_M^n and work on simulations of neutron detection in the CLAS12 detector to prepare for the 12-GeV G_M^n experiment (see Section 3).

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. To put our understanding of the NN force on firmer footing, we are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e}, e'p)n$ with CLAS in quasielastic (QE) kinematics [10]. In particular, the so-called fifth structure function is nonzero only outside the plane defined by the incoming and scattered electron. This structure function has been rarely measured and never at these kinematics. To study the fifth structure function we use an asymmetry $A'_{LT} = \sigma'_{LT}/(\sigma_L + \sigma_T)$ where σ'_{LT} is the partial cross section for the fifth structure function and σ_L and σ_T are the longitudinal and transverse partial cross sections respectively. This asymmetry has been extracted over the range $Q^2 = 0.2 - 5.0$ $(\mathrm{GeV/c})^2$ [10, 27]. 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 a study of the radiative corrections and discovered that, contrary to expectations, the adjustment to A'_{LT} is significant for some kinematics (small $\vec{p}_m$ and ϕ_{pq} near 180°). We are now incorporating those corrections into our analysis. A draft of the analysis note is nearly complete and will be submitted for review in the next budget period.[4] 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.

QCD directs the formation of hadrons from quarks and gluons in hard scattering. However, there is no full, QCD-based theory to explain hadronization and fragmentation. The Electron-Ion Collider (EIC) has been proposed as the next-generation facility for nuclear physics to probe these questions and others [31]. In 2010, one of the organizers of the EIC nuclear Chromo-dynamic group (K.Hafidi) invited us to explore the measurement of correlations between bosons (*e.g.* $\pi^+\pi^+$) to study the space-time extent of the source of the particles and/or learn about the dynamics of their formation. These Bose-Einstein Correlations (BEC) occur when particles are formed near one another so their wave functions overlap and interfere; producing correlations in the intensity and momentum dependence of the final particles. For example, the difference in the longitudinal and transverse (relative to the momentum transfer) size of the emitting source in eA collisions may reveal the properties of the QCD 'string' in nuclear matter [32].

We have simulated $\pi^+\pi^+$ BECs from eA collisions at EIC kinematics using the code PYTHIA [33]. This program includes options to include BECs in the simulation and they show significant correlations at $Q_{12} \approx 0$ where Q_{12} is the magnitude of the 4-momentum difference between the two pions. Parameters were taken from measurements at ZEUS [34]. A significant correlation here implies that a large fraction of the pions are correlated in the source. To explore longitudinal and transverse differences in the BECs we used the Longitudinal Center-of-Mass System and found a significant difference in the L and T correlations functions at $Q_{12} = 0$ [32]. Our simulations show that we can expect to extract the sources sizes down to a resolution of about $0.1 - 0.2\ fm$. Bose-Einstein Correlations are a promising tool for studying the properties of nuclear matter at the EIC.

The confinement of quarks inside hadrons is perhaps the most remarkable feature of QCD and understanding it is an essential goal of nuclear physics [35]. The nuclear dependence of particle production reveals features of quark motion in nuclear matter and the formation of hadrons. Experiment E12-06-117 is part of the 12-GeV Upgrade with a scientific rating of A- and an allocation of 30 days of beamtime [17, 18, 16]. Gilfoyle is a co-spokesperson and will be responsible for analyzing the π^0, η, and η' production.

[4] The first step to publish CLAS results is for an internal Collaboration committee to review a report describing the technical details of the analysis.

3 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 [36]. 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) [37]. Neutron events were simulated with gemc and Socrat was modified to include neutral hits from the TOF system in the datastream. We have studied the outer TOF in particular because it will re-use existing CLAS6 TOF panels and we have compared the simulated efficiency with the measured one. Our results are roughly consistent with the measured neutron efficiency in CLAS6, but are sensitive to the detection threshold in the TOF panels [26]. This study is ongoing. We have also implemented the forward electromagnetic calorimeter (EC) system of the current CLAS6 detector in gemc where it will be reused in CLAS12. The early results show the expected behavior for the energy deposited in the EC when compared with CLAS6 [38]. We have recently streamlined the geometry model to make the code more robust and ganged together different layers of the light-emitting scintillators to reproduce the structure of the detector [25]. We have also modified the reconstruction code Socrat to include the EC information in its output event format. The study of the simulated behavior of the EC is ongoing. In the next year we expect to reconstruct the EC neutral events in Socrat, and extract the neutron efficiency.

In 2010 we purchased a new high-performance computing cluster from Advanced Clustering in Kansas City, Kansas with funds from an NSF Major Research Instrumentation grant. The cluster consists of a single head node with twenty remote nodes each with twelve cores. After installation and commissioning in the summer of 2010 we began using the cluster during the summer for physics analysis [24]. This cluster has become a development and test platform for service-oriented architecture. This software method holds the promise of creating a robust, accessible, and distributed system for the analysis of CLAS12 data.[39]

Gilfoyle maintains a program for calculating radiative corrections for the exclusive reaction $D(e, e'p)n$ [40] using a method developed by Afanasev, *et al.* [41] and deuteron response functions calculated with the program DEEP [42, 43]. 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 [44].

4 CLAS Collaboration Service Work

Gilfoyle completed his term 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. He was chair of the organizing committee of the CLAS12 Software Workshop that was held at the University of Richmond May 25-26, 2010. The Workshop was funded by JSA/SURA, the University of Richmond, and Christopher Newport University who provided funds for travel for the speakers and students and postdocs and other expenses [45]. Approximately 50 people attended the plenary session on May 25. The plenary speakers in the morning session were Michael Ernst (Brookhaven), Elena Gerchtein (FNAL), Chip Watson (JLab), and Graham Heyes (JLab). The focus was on the state of the art of the analysis of large physics data sets and the future of computing at Jefferson Lab after the 12 GeV Upgrade. In the afternoon speakers from the CLAS Collaboration and the other experimental halls discussed current projects and plans for the future of the CLAS12 software enterprise. The next day tutorials to learn how to use the existing CLAS12 software and to demonstrate CLARA ([39]) were held and about 25 people attended. Feedback from the participants including JLab administrative staff was very positive. Since then the members of the Hall D collaboration held a similar workshop at Christopher Newport University.

Summary of Contract-Related Activities

Refereed Publications

1. H. Baghdasaryan et al. Tensor Correlations Measured in $^3He(e, e^{'}pp)n$. *Phys. Rev. Lett.*, 105(22):222501, Nov 2010.

2. B. Dey et al. Differential cross sections and recoil polarizations for the reaction $\gamma p \to K^+\Sigma^0$. *Phys. Rev. C*, 82(2):025202, Aug 2010.

3. M. H. Wood et al. Absorption of the ω and ϕ Mesons in Nuclei. *Phys. Rev. Lett.*, 105(11):112301, Sep 2010.

4. H. Avakian et al. Measurement of Single- and Double-Spin Asymmetries in Deep Inelastic Pion Electroproduction with a Longitudinally Polarized Target. *Phys. Rev. Lett.*, 105(26):262002, Dec 2010.

5. M. E. McCracken et al. Differential cross section and recoil polarization measurements for the $\gamma p \to K^+\Lambda$ reaction using CLAS at Jefferson Lab. *Phys. Rev. C*, 81(2):025201, Feb 2010.

6. X. Qian et al. Near-threshold photoproduction of ϕ mesons from deuterium. *Phys. Lett. B*, 696(4):338–342, Feb 2011.

7. S. Anefalos Pereira et al. Differential cross section of $\gamma n \to K^+\Sigma^-$ on bound neutron with incident photons from 1 to 3.6 GeV. *Phys. Lett. B*, 688(4-5):289–293, May 2010.

8. M. Osipenko et al. Measurement of the Nucleon Structure Function F2 in the Nuclear Medium and Evaluation of its Moments. *Nucl. Phys. A*, 845(1-4):1–32, Nov 2010.

9. Y. Ilieva et al. Evidence for a backward peak in the $\gamma + d \to \pi^0 + d$ cross section near the eta threshold. *Eur. Phys. Jour. A*, 43(3):261–267, 2010.

Other Publications

G.P. Gilfoyle et al. Measuring the Magnetic Form Factor of the Neutron in CLAS12 in *Proceedings of the Workshop on Exclusive Reactions at High Momentum Transfer IV*, World Scientific, 2011.

Invited Talks

1. G.P. Gilfoyle, 'From Quarks to the Bomb', University of Richmond, Nov. 10, 2010.

2. G.P. Gilfoyle, 'Bose-Einstein Correlations at the Electron-Ion Collider', Institute for Nuclear Theory, University of Washington, October 12, 2010.

3. G.P. Gilfoyle, 'Few-Body Physics with CLAS', 21st European Conference on Few-Body Problems in Physics, University of Salamanca, Aug 30, 2010.

4. G.P. Gilfoyle, 'Measuring the Magnetic Form Factor of the Neutron in CLAS12', Workshop on Exclusive Reactions at High Momentum Transfer IV, Jefferson Lab, May 19, 2010.

5. G.P. Gilfoyle, 'Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation', Joint Meeting of the New England and the New York State Sections of the American Physical Society: Modern Nuclear Applications, Union College, April 24, 2010.

Contributed talks and posters.

1. C.Musalo, J.Carbonneau, and G.P.Gilfoyle, 'Simulation of the CLAS12 Forward Electromagnetic Calorimeter', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00077 (2010), poster.

2. J. Carbonneau and G.P.Gilfoyle, 'Development of a Computing Cluster At the University of Richmond', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00018 (2010), poster.

3. M.Moog, J. Carbonneau, and G.P.Gilfoyle, 'Simulating the Neutron Detection Efficiency of the CLAS12 Detector', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00073 (2010), poster.

4. G.P.Gilfoyle, 'Report on the CLAS12 Software Workshop', CLAS Collaboration Meeting, Jefferson Lab, June 17, 2010.

5. G.P.Gilfoyle, 'Simulation Results for CLAS12 From gemc', CLAS12 Software Workshop, Jefferson Lab, May 25, 2010.

6. G.P.Gilfoyle, 'Report to the CLAS Collaboration on the Nuclear Physics Working Group meeting', Jefferson Lab, March 20, 2010

7. G.P.Gilfoyle, 'Report to the CLAS Collaboration on the CLAS12 Software meeting', plenary session, Jefferson Lab, March 18, 2010.

8. G.P.Gilfoyle, 'Recent Progress Implementing the Electromagnetic Calorimeter in the CLAS12 Geant4 simulation (gemc)', Jefferson Lab, March 17, 2010.

Service Work

1. Chair, Nuclear Physics Working Group and member of the CLAS Coordinating Committee (term completed).

2. Chair, Organizing Committee, CLAS12 Software Workshop held at the University of Richmond, May 25-26, 2010.

3. Reviewer, National Science Foundation, Nuclear Physics Program, Physics Division, Directorate for Mathematical and Physical Sciences.

4. Reviewer, Department of Energy, Medium Energy Nuclear Physics Program, Office of Nuclear Physics.

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