Continuation Progress Report

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Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period January 1, 2012 to February 13, 2013 under contract number DE-FG02-96ER40980 entitled *Nuclear and Particle Physics at the University of Richmond*, Gerard P Gilfoyle (PI).[1] See pages 7-8 for a summary. The experimental work 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 at the University of Richmond (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 currently working on software for the simulation, reconstruction, and analysis of data to be collected with the new CLAS12 detector in Hall B after the completion of the 12 GeV Upgrade.[2] He is spokesperson on a CLAS Approved Analysis *Out-of-Plane Measurements of Deuteron Structure Functions* [10].[3] 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 [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]. 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]. During the period of this report Gilfoyle was invited to give a talk on JLab physics [19], and a seminar on physics and science policy [20]. Last summer, three undergraduates (Keegan Sherman, Liam Murray, and Spencer Bialt) worked in Gilfoyle's nuclear physics lab at the University of Richmond. Two of these undergraduates were supported by the grant and one was supported by other University of Richmond funds. Two of the University of Richmond undergraduates presented their work at the Fall, 2012 meeting of the DNP [21, 22]. Our laboratory at the Richmond was enhanced with the completion of the acquisition of a new computing cluster obtained with grant funds from the National Science Foundation Major Research Instrumentation program.

We anticipate there will be about $11,400 remaining in unexpended funds in the student stipend, equipment, and travel categories at the end of the current budget period. Most of the funds ($7,000) were designated for purchasing Graphical Processing Units(GPUs) to study how they would be used for CLAS12 software development. However, the CLAS12 software program was the subject of an external review in June, 2012 and one of the recommendations was to perform a 'stress test' of the entire CLAS12 analysis chain during 2013. With our collaborators in the CLAS12 Software Group we are focusing our efforts on that task and have put off purchasing the GPUs until we can devote appropriate resources. We have also obtained University of Richmond support for undergraduate stipends. This allows us to stretch the summer stipends further (Keegan Sherman worked an additional two weeks last summer on the CLAS12 geometry database) and there is $2,400 in student stipends left from the summer of 2012. We were also able to obtain support for conference travel from the University of Richmond and the American Physical Society (for Gilfoyle and two undergraduates). The University of Richmond supported routine travel to JLab. 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) that characterize the distributions of charge and magnetization within the proton and neutron. We are part

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[2] 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, CLAS12, to take advantage of the new physics opportunities.

[3] A CLAS Collaboration member can write a proposal to analyze existing, 6-GeV CLAS (CLAS6) data which is reviewed by a committee of Collaboration members, and defended before the Collaboration who then vote to approve it.

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 E94-017 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 $^2H(\vec{e}, e'p)n$ 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 using a $\sin\phi_{pq}$-weighted technique over the range $Q^2 = 0.2 - 2.0$ $(GeV/c)^2$ where ϕ_{pq} is the angle between the scattering plane defined by the incoming and outgoing electron and the reaction plane defined by the electron momentum transfer and the measured proton 3-momentum [10, 24]. During the period of this report we significantly revised our selection of quasielastic events to reduce bias associated with using the W, the residual mass calculated only from the scattered electron information. We now use the measured electron and proton information to get a cleaner selection of quasielastic, final-state neutrons. Our preliminary results for A'_{LT} show significant structure which is reproduced by a recent calculation at low Q^2 from Jeschonnek and van Orden and disagrees with others [25, 26, 27]. For the high Q^2 data set none of the calculations reproduce the data. We improved the comparison between our data and the calculation by Jechonnek and van Orden by obtaining calculations of a full range in Q^2, missing momentum p_m, and Bjorken x. These calculations were then averaged over the measured Q^2 and Bjorken x distributions of our data. We have also redone the determination of the systematic uncertainties and measured the errors on thirteen different cuts and constraints. We have also extracted A'_{LT} in a different way using fits to the dependence of the asymmetry on ϕ_{pq} and found agreement with the $\sin\phi_{pq}$-weighted technique.[22] We have completed a draft of an analysis note describing this work and submitted it for CLAS Collaboration review.[4] The work was also presented at the most recent CLAS Collaboration meeting in October, 2012.[24] 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.

The confinement of quarks inside hadrons is perhaps the most remarkable feature of QCD and understanding it is an essential goal of nuclear physics [28]. 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.

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 [29]. We will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction in the new Hall-B detector CLAS12. During the period of this report we have continued developing the geometry for the simulation of the CLAS12 electromagnetic calorimeter (EC) which is being reused from CLAS6. The EC will be used in Experiment E12-07-14 for neutron detection. The CLAS12 simulation package *gemc* is

[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.

a C^{++} framework based on Geant4 Libraries to simulate the passage of particles through matter. Detector parameters such as geometry, materials, output format, sensitivity, *etc.* are stored in a database so that numbers are not hardcoded in the source. Our original implementation of the EC in *gemc* is described in CLAS-NOTE 2011-019.[30] The EC consists of alternating layers of lead and scintillator and the scintillator layers have been simulated as one large, triangular piece of material (there are 39 scintillator layers). In reality, each scintillator layer consists of 36 strips that form the final layer. This approximation to the geometry was done to speed the simulation. During the period of this report we revised the EC geometry so that the scintillator layers now consist of 36 strips.[21] In our tests we found little change in the physics output by comparing the distribution of EC hits from electrons in the range $E = 1 - 10$ GeV before and after the changes. The impact on batch processing of events varied from a small increase in computing time ($\approx 1\%$) for low (1 GeV) electrons to a 5% increase at 10 GeV. The *gemc* program includes a sophisticated graphics component that gives the user a full three-dimensional view of CLAS12 and the trajectories of the particles and allows one to manipulate that image. This is where the switch to strips had a large impact. We found the graphics performance slowed by about 30%. The graphics package is still usable, but there was now a noticeable change in the response time. One of our collaborators (Cole Smith) added layers of foam and aluminum to simulate the upstream face of the EC, *i.e.* the cover of the box holding the detector components. We also resolved an old problem with the position of the EC relative to the target. The problem was related to a bug in the code and a significant difference between the original description of the CLAS6 and the existing design. During the period of this report, we took the first steps investigating the use of Graphical Processing Units (GPUs) for running CLAS12 software. We have two GPUs in our laboratory at Richmond and students have been learning how to write codes on them. This project is ongoing.

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. During the period of this report we have completed installation of the cluster. It now consists of a single head node with 32 remote nodes (versus the original twenty in 2010) each with twelve cores. This cluster has become a development and test platform for service-oriented architecture CLARA that is being developed by the CLAS12 Software Group. This software method holds the promise of creating a robust, accessible, and distributed system for the analysis of CLAS12 data.

Gilfoyle maintains a program for calculating radiative corrections for the exclusive reaction $D(e, e'p)n$ [31] using a method developed by Afanasev, *et al.* [32] and deuteron response functions calculated with the program DEEP [33, 34]. 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 [35]. With the completion of the CLAS6 program in 2012, this code will be retired.

4 Professional and CLAS Collaboration Service Work

Gilfoyle was co-author of the documentation prepared for an external review of the CLAS12 software program in June, 2012. The committee reviewed the state of software and computing developments for the 12 GeV program at Jefferson Lab with particular emphasis upon detector simulation, calibration, and event analysis and workflow tools for production analysis. Gilfoyle was responsible for estimating the computing requirements for CLAS12 which included the needs for processing power for data acquisition, calibration, reconstruction, simulation, and analysis. He also evaluated the storage needs for long-term storage and for physics processing of the data. The final report is in Ref. [23].

Gilfoyle served on six review committees during this period. He was chair of two *ad hoc* reviews of drafts of papers for submission to be published.[5] He also wrote reviews of two grant proposals for the Office of Nuclear Physics of the DOE Office of Science and two more for the Experimental Nuclear Physics program at the National Science Foundation.

[5] As part of the procedure for publishing CLAS results, an internal Collaboration committee reviews the paper after the analysis is approved.

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Summary of Contract-Related Activities

Refereed Publications

1. H. Egiyan, J. Langheinrich, R. W. Gothe, L. Graham, M. Holtrop, H. Lu, P. Mattione, G. Mutchler, K. Park, E. S. Smith, S. Stepanyan, Z. W. Zhao, et al. Upper limits for the photoproduction cross section for the $\phi(1860)$ pentaquark state off the deuteron. *Phys. Rev. C*, 85:015205, Jan 2012.

2. N. Baillie, S. Tkachenko, J. Zhang, P. Bosted, S. Bültmann, M. E. Christy, H. Fenker, K. A. Griffioen, C. E. Keppel, S. E. Kuhn, W. Melnitchouk, V. Tvaskis, et al. Measurement of the neutron F_2 structure function via spectator tagging with clas. *Phys. Rev. Lett.*, 108:142001, Apr 2012.

3. M. Anghinolfi et al. Comment on "observation of a narrow structure in ^{1}h(γ,K^0_S)x via interference with ϕ-meson production". *Phys. Rev. C*, 86:069801, Dec 2012.

4. D. Keller, K. Hicks, et al. Branching ratio of the electromagnetic decay of the $\sigma^+(1385)$. *Phys. Rev. D*, 85:052004, Mar 2012.

5. K. Park, R. W. Gothe, et al. Measurement of the generalized form factors near threshold via $\gamma^* p \rightarrow \mathrm{n}\pi^+$ at high Q^2. *Phys. Rev. C*, 85:035208, Mar 2012.

6. H. Baghdasaryan, L. B. Weinstein, J. M. Laget, et al. Comparison of forward and backward pp pair knockout in $^3he(e,e'pp)n$. *Phys. Rev. C*, 85:064318, Jun 2012.

7. V. I. Mokeev, V. D. Burkert, L. Elouadrhiri, G. V. Fedotov, E. N. Golovatch, R. W. Gothe, B. S. Ishkhanov, E. L. Isupov, et al. Experimental study of the $P_{11}(1440)$ and $D_{13}(1520)$ resonances from the clas data on $ep \rightarrow e'\pi^+\pi^- p'$. *Phys. Rev. C*, 86:035203, Sep 2012.

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9. L. El Fassi et al. Deep exclusive π^+ electroproduction off the proton at clas. *Eur. Phys. J. A*, 49:16, 2013.

Other Publications

D.Weygand et al. 'CLAS12 Software Document - Hall B 12 GeV Upgrade', Jefferson Lab Report, May, 2012.

Invited Talks

1. G.P. Gilfoyle, 'Hunting for Quarks', University of Virginia, January 20, 2012.

2. G.P. Gilfoyle, 'Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation', University of Virginia, January 20, 2012.

Contributed talks and posters.

1. L.Murray and G.P.Gilfoyle, ' Extracting the Fifth Structure Function of the ^{2}H(e, e′p)n Reaction', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00114 (2012), poster.

2. K.Sherman and G.P.Gilfoyle, 'Simulation of the Scintillator Geometry in the Electromagnetic Calorimeter in the CLAS12 Detector', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00115 (2012), poster.

3. G.P.Gilfoyle, 'Measuring the Fifth Structure Function in ^{2}H(e, ep)n', CLAS Collaboration Meeting, Jefferson Lab, October 12, 2012.

4. V.Burkert et al. NSAC Review of the CLAS12 Program, Jefferson Lab, August, 2012.

Service Work

1. Reviewer, CLAS Collaboration, chair of two review committees.

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

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

Proposals

G.P.Gilfoyle, 'Supplemental Grant Request to Medium Energy Nuclear Physics Research at the University of Richmond', (Request to fund a joint University of Richmond/University of Surry masters student), US DOE, approved July, 2012.