Continuation Progress Report

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Title: Nuclear and Particle Physics Research at the University of Richmond

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Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period January 1, 2013 to December 31, 2013 under contract number DE-FG02-96ER40980 entitled *Nuclear and Particle Physics at the University of Richmond*, Gerard P Gilfoyle (PI).[1] See pages 6-7 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 eight refereed articles during this period [1, 2, 3, 4, 5, 6, 7, 8]. He is currently working on physics analysis projects described below and 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] Gilfoyle is spokesperson and contact person on a new experiment to measure the neutron magnetic form factor G_M^n in Hall B entitled *Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on Deuterium* (JLab experiment E12-07-104) that will run in the first five years after the 12 GeV Upgrade at JLab [9, 10]. The experiment was assigned a scientific rating of A^- by PAC35 in January, 2010 and 30 days of beamtime were allocated [11, 12]. Gilfoyle is co-spokesperson on another JLab 12-GeV proposal to measure G_M^n in Hall A entitled *Precision Measurement of the Neutron Magnetic Form Factor at* $Q^2 = 16.0$ *and* 18.0 $(GeV/c)^2$ *by the Ratio Method* (JLab experiment E12-09-019). He is also co-spokesperson on a JLab 12-GeV proposal entitled *Quark Propagation and Hadron Formation* (JLab experiment E12-06-117) that was approved by PAC30 [13, 14]. Current physics projects include the analysis of existing data from CLAS6 experiment E94-017 to measure the magnetic form factor of the neutron or G_M^n [15]. CLAS6 is the previous detector in Hall B. The results for two out of three sets of run conditions have been published [16] and his group continues work on the third set. He is spokesperson on a CLAS6 Approved Analysis *Out-of-Plane Measurements of Deuteron Structure Functions* to extract the fifth structure function of the deuteron [17].[3]

During the period of this report Gilfoyle was invited to give talks on JLab physics at the *Workshop on High-Energy Physics in the LHC Era* [18] and Hall B software development during an external review of the JLab software enterprise [19]. He also presented the group's program at the DOE Comparative Review [20, 21]. In the last year Gilfoyle mentored a masters student, Alex Colvill, from the University of Surrey in the UK who wrote the reconstruction software for the time-of-flight (TOF) systems in CLAS12 [22, 23]. Mr. Colvill is part of a joint Surrey/Richmond program where a Surrey masters student fulfills his/her requirement to spend a year doing physics research under Gilfoyle's guidance at Jefferson Lab. He was supported by a supplemental grant from DOE. Last summer three undergraduates, Keegan Sherman, Liam Murray, and Justin Ruger, worked under Gilfoyle's guidance at Richmond and JLab. Mr. Ruger also worked closely with one of the JLab staff scientists Dr. Dennis Weygand. Two of these undergraduates were supported by the DOE grant and one was supported by other University of Richmond funds. Two of the undergraduates presented their work at the Fall, 2013 meeting of the Division of Nuclear Physics (DNP) of the APS [24, 25]. Our laboratory at Richmond was enhanced with the purchase of an Intel Xeon MIC (Many Integrated Co-processors) with DOE funds. We used this machine to investigate it potential as a tool for CLAS12 analysis.

We anticipate that at the end of the current budget period (May 31, 2014) there will be about $26,000 remaining in unexpended funds with about $1,100 in students stipends and the rest in the travel and equipment categories. See the budget justification for more details. In the past, we have routinely 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 to build code on the Intel Xeon MIC). 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). We will use these unexpended funds to support additional students and travel in the future. The University of Richmond supported routine travel to JLab. As usual, undergraduates were involved in all aspects of our work. Below, we discuss recent accomplishments and describe plans for the next budget period.

[1] Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173.

[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.

2 Physics Projects

The elastic electromagnetic form factors are 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 and our focus is on G_M^n, the magnetic form factor of the neutron. As part of that effort we are analyzing an existing CLAS6 data set using the same methods that will be used for the proposed experiments (E12-07-104 and E12-09-019) mentioned in the Introduction. 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 [16]. In the last year we have rebuilt the software (written about 2005) used to analyze those first two data sets and have it operating on the Richmond cluster. We were able to reproduce some of the analysis such as the neutron detection efficiency of the first two data sets and continue to test the code and update the software so it runs properly on current machines. The event generator used to simulate the reaction in CLAS6 has been resurrected and is being used for this study and the analysis of the fifth structure function of the deuteron (see description below).

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 CLAS6 in quasielastic (QE) kinematics [17]. 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 $Q^2 = 0.2 - 2.0$ $(\mathrm{GeV/c})^2$ 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 [17, 26]. We submitted a draft analysis note in late 2012.[4] We have generated two rounds of responses raised by the review committee and have begun revising some of our Monte Carlo calculations in response to committee recommendations. In the simulations we characterize the asymmetry A'_{LT} by fitting a polynomial to our measured results and use that function to generate Monte Carlo events with the same shape. These generated events are passed through the standard CLAS6 simulation GSIM and then analyzed with the same codes used to analyze the data. We find that so far the Monte Carlo validates the accuracy of our analysis programs. This work was the subject of an undergraduate summer project and poster at the fall, 2013 meeting of the DNP [24].

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 [27]. We are 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 developed the reconstruction code for the two TOF sub-systems of CLAS12. The reconstruction of these CLAS12 data is a challenging software project - The CLAS12 Forward Detector is built around a toroidal magnet and consists of layers of Cherenkov counters, drift chambers, TOF counters, and calorimeters. It has six, identical, independent sectors that cover a large solid angle with about 28,000 readouts. The TOF sub-system has 540 scintillator paddles in the TOF sub-system arranged in three separate panels in each of six sectors with 1080 readouts (one for each end of the paddle). A large-angle device (the Central Detector) is based on a solenoid magnet using a silicon vertex tracker and TOF system with nearly 34,000 readouts. The TOF sub-system here has 48 paddles with 96 readouts (one for each end of the paddle). CLAS12 will collect about five TByte of data each day that will require reconstruction and simulation. The TOF sub-systems will produce fast timing signals

[4] The first step to publish CLAS6 results is for an internal Collaboration committee to review a report describing the technical details of the analysis.

that, when combined with the measured trajectory of the particle, can be used to accurately determine the time-of-flight of the detected particle - a crucial element of the particle identification. When the data from an event are first analyzed, each component of the software system performs a standalone analysis. For the TOF systems, photo-multiplier (PMT) signals are collected (one from each end of the PMT) and the timing signals, positions, and deposited energy in each scintillator paddle are extracted. Clusters of adjacent hits are identified for later use. Calculating the time-of-flight is done later when tracking information is available. In the last year Alex Colvill, the masters student from Surrey, worked on this project under the guidance of the PI (Gilfoyle) and the other members of the CLAS12 software group. Starting from the Fortran code used in the CLAS6 Forward Detector analysis, the algorithm for the CLAS12 Forward Detector has been written in Java and incorporated into CLARA, the CLAS12 reconstruction environment. CLARA is part of an innovative service-oriented architecture (SOA) developed in Hall B for reconstruction that is robust, modular and takes full advantage of modern distributed and multi-threaded environments [28]. This Java code has been made been made readily configurable (the old TOF code had many hard-wired parameters) and validated with simulations performed with the CLAS12 standard simulation *gemc*. The simulations were run on the Richmond cluster using deep-inelastic scattering kinematics with many different final particle states. We compared simulations at CLAS6 energies (5.7 GeV) with ones at CLAS12 energies (11 GeV), with and without beam-related backgrounds or scattering from other CLAS12 hardware components. We investigated different methods for forming clusters of adjacent paddles with hits and have evidence for a better method to form clusters. In the CLAS6 algorithm, for example, a multiple of the time difference between paddles relative to the uncertainty in the individual time measurements was used as a cut-off to determine which paddles should be grouped into a cluster. We found that an absolute time difference was more efficient at identifying true clusters. The optimal choice of the parameters was determined using a wide range of simulations. The reconstruction code for the TOF system in the Central Detector is similar to the Forward Detector and that code has been written, tested, and optimized is a similar way. The code was part of the stress test in fall, 2013 where the full analysis chain available at the time was distributed over many compute nodes in the JLab farm and simulation data were analyzed for several days. The TOF code worked without error. A CLAS-NOTE on this work is in preparation.

In the last year we obtained an Intel Xeon Phi co-processor with DOE funds. It uses the MIC (Many Integrated Coprocessors) architecture to perform parallel computations. It is a competitor to the Graphical-Processing Units (GPUs) that perform the same function, but the MIC is easier to program (a significant barrier in using the GPUs). Two undergraduates programmed the MIC last summer. One student, Justin Ruger, adapted an existing algorithm that performs a partial-wave analysis to work on the MIC and saw a considerable increase in speed. The other student, Keegan Sherman, was able to build and run the CERN analysis code ROOT on the MIC. The performance improvement here was limited. This project is ongoing. Mr. Ruger's work was the subject of a poster at the fall meeting of the DNP [25].

The Richmond cluster (obtained in 2010 with NSF funds) continues to be a major development tool for the CLAS12 software group especially for CLARA [28]. In the last year the operating system on the cluster was updated (using University of Richmond funds) to keep it synchronized with the JLab farm.

Gilfoyle continues to work on software planning for CLAS12. The software effort for the entire Laboratory was assessed in November, 2013 by an external panel. Gilfoyle gave a presentation on the CLAS12 software user environment [19]. He was responsible for updating the estimates of the computing requirements for CLAS12 which included the needs for processing power for data acquisition, calibration, reconstruction, simulation, analysis, and storage.

4 Professional and CLAS Collaboration Service Work

Gilfoyle was chair of four CLAS Collaboration review committees in the last year. Three reviews were *ad hoc* ones of drafts of papers for submission to be published.[5] The other review considered an analysis of the $^2H(\tilde{e}, e'p)n$ reaction. He also wrote a review of one grant proposals for the Experimental Nuclear Physics program at the National Science Foundation and served as chair of the CLAS Collaboration chair nominating committee.

[5]As part of the procedure for publishing CLAS6 results, an internal Collaboration committee reviews the paper after the analysis is approved. the draft then goes to the full Collaboration for final approval.

References

[1] M. Moteabbed et al. Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering. *Phys.Rev.*, C88:025210, 2013.

[2] K. Moriya et al. Differential Photoproduction Cross Sections of the $\Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$. *Phys.Rev.*, C88:045201, 2013.

[3] W. Tang et al. Cross sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ reactions measured at CLAS. *Phys.Rev.*, C87:065204, 2013.

[4] K. Moriya et al. Measurement of the photoproduction line shapes near the (1405). *Phys.Rev.*, C87(3):035206, 2013.

[5] M. Anghinolfi, J. Ball, N.A. Baltzell, M. Battaglieri, I. Bedlinskiy, et al. Comment on 'Observation of a narrow structure in $p(\gamma, K_S)X$ via interference with ϕ-meson production'. *Phys.Rev.*, C86:069801, 2012.

[6] O. Hen et al. Measurement of transparency ratios for protons from short-range correlated pairs. *Phys.Lett.*, B722:63–68, 2013.

[7] P. Khetarpal et al. Near Threshold Neutral Pion Electroproduction at High Momentum Transfers and Generalized Form Factors. *Phys.Rev.*, C87(4):045205, 2013.

[8] K. Park et al. Deep exclusive π^+ electroproduction off the proton at CLAS. *Eur.Phys.J.*, A49:16, 2013.

[9] G.P. Gilfoyle, W.K. Brooks, S. Stepanyan, M.F. Vineyard, S.E. Kuhn, J.D. Lachniet, L.B. Weinstein, K. Hafidi, J. Arrington, D. Geesaman, R. Holt, D. Potterveld, P.E. Reimer, P. Solvignon, M. Holtrop, M. Garcon, S. Jeschonnek, and P. Kroll. Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium. E12-07-104, Jefferson Lab, Newport News, VA, 2007.

[10] JLab Physics Advisory Committee. PAC32 Report. Technical report, Jefferson Laboratory, 2007.

[11] G.P. Gilfoyle, W.K. Brooks, K. Hafidi, et al. Update for E12-07-104: Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium. Technical report, Jefferson Lab, Newport News, VA, 2010.

[12] JLab Physics Advisory Committee. PAC35 Report. Technical report, Jefferson Laboratory, 2010.

[13] K. Hafidi, J. Arrington, L. El Fassi, D.F. Geesaman, R.J. Holt, B. Mustapha, D.H. Pottervel, 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, and G.P. Gilfoyle. Quark propagation and hadron formation. E12-06-117, Jefferson Lab, Newport News, VA, 2006.

[14] JLab Physics Advisory Committee. Pac30 report. Technical report, Jefferson Laboratory, 2006.

[15] W. Brooks and M.F. Vineyard. The neutron magnetic form factor from precision measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium. Proposal e94-017, Jefferson Lab, Newport News, VA, 1994.

[16] 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. `http://link.aps.org/abstract/PRL/v102/e192001`.

[17] G.P. Gilfoyle (spokesperson), W.K. Brooks, B.A. Mecking, S.E. Kuhn, L.B.Weinstein, and M.F. Vineyard. Out-of-plane measurements of the structure functions of the deuteron. CLAS Approved Analysis, 2003. `http://www.jlab.org/Hall-B/general/clas_approved_analyses.htm`.

[18] G.P. Gilfoyle. Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab. Presented at the Workshop on High-Energy Physics in the LHC Era, December 17, 2013.

[19] G.P. Gilfoyle. Hall B: Software Utilization. Presented at the 12 GeV Software Review, November 25, 2013.

[20] G.P. Gilfoyle. Nuclear and Particle Physics at the University of Richmond. Briefing materials for the Medium Energy subfield review of the Office of Nuclear Physics Comparative Research Review, 2013.

[21] G.P. Gilfoyle. Nuclear and Particle Physics at the University of Richmond. Presented at the Medium Energy subfield review of the Office of Nuclear Physics Comparative Research Review, June 13, 2013.

[22] A. Colvill and G.P. Gilfoyle. Forward Time of Flight Reconstruction Software for CLAS12. In *Bull. Am. Phys. Soc., Fall SESAPS Meeting*, 2013.

[23] A Colvill. Time of flight software for the clas12 particle detector. Master's thesis, University of Surrey, in preparation.

[24] L. Murray and G.P. Gilfoyle. Validating the Analysis Algorithms to Extract the Helicity Asymmetry in the 2H(e ,ep)n Reaction. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2013.

[25] J. Ruger, G.P. Gilfoyle, and D. Weygand. Applicability of Parallel Computing to Partial Wave Analysis. In *Bull. Am. Phys. Soc., Fall DNP Meeting*, 2013.

[26] G.P. Gilfoyle. Measuring the Fifth Structure Function in $^2\mathrm{H(e,ep)n}$. CLAS Collaboration Meeting, October 12, 2012.

[27] Pre-Conceptual Design Report (pCDR) for The Science and Experimental Equipment for The 12 GeV Upgrade of CEBAF. Technical report, Jefferson Lab, Newport News, VA, 2004.

[28] V. Gyurjyan, D. Abbott, G.P. Gilfoyle, J. Carbonneau, G. Heyes, S. Paul, C. Timmer, D. Wyegand, and E. Wolin. CLARA: A Contemporary Approach to Physics Data Processing. *J.Phys.Conf.Ser.*, 331, 2011.

Summary of Contract-Related Activities

Refereed Publications

1. M. Moteabbed et al. Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering. *Phys.Rev.*, C88:025210, 2013.

2. K. Moriya et al. Differential Photoproduction Cross Sections of the $\Sigma^0(1385)$, $\Lambda(1405)$, and $\Lambda(1520)$. *Phys.Rev.*, C88:045201, 2013.

3. W. Tang et al. Cross sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ reactions measured at CLAS. *Phys.Rev.*, C87:065204, 2013.

4. K. Moriya et al. Measurement of the photoproduction line shapes near the (1405). *Phys.Rev.*, C87(3):035206, 2013.

5. M. Anghinolfi, J. Ball, N.A. Baltzell, M. Battaglieri, I. Bedlinskiy, et al. Comment on 'Observation of a narrow structure in $p(\gamma, K_S)X$ via interference with ϕ-meson production'. *Phys.Rev.*, C86:069801, 2012.

6. O. Hen et al. Measurement of transparency ratios for protons from short-range correlated pairs. *Phys.Lett.*, B722:63–68, 2013.

7. P. Khetarpal et al. Near Threshold Neutral Pion Electroproduction at High Momentum Transfers and Generalized Form Factors. *Phys.Rev.*, C87(4):045205, 2013.

8. K. Park et al. Deep exclusive π^+ electroproduction off the proton at CLAS. *Eur.Phys.J.*, A49:16, 2013.

Other Publications and Reports

G.P. Gilfoyle, Nuclear and Particle Physics at the University of Richmond, Briefing materials for the Medium Energy subfield review of the Office of Nuclear Physics Comparative Research Review, 2013.

Invited Talks

1. G.P. Gilfoyle, 'Hall B: Software Utilization', 12 GeV Upgrade Software Review, Jefferson Lab, November 25, 2013.

2. G.P. Gilfoyle, 'Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab', Workshop on High-Energy Physics in the LHC Era, Valparaiso, Chile, Dec 17, 2013.

Contributed talks and posters.

1. L.Murray and G.P.Gilfoyle, 'Validating the Analysis Algorithms to Extract the Helicity Asymmetry in the 2H(e ,ep)n Reaction', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00173 (2013), poster.

2. J.Ruger, G.P.Gilfoyle, and D.Weygand, 'Applicability of Parallel Computing to Partial Wave Analysis', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00172 (2013), poster.

3. A.Colvill and G.P.Gilfoyle, 'Forward Time of Flight Reconstruction Software for CLAS12', Bull. Am. Phys. Soc., Fall SESAPS Meeting, KA.00060 (2013), poster.

Other Presentations

G.P. Gilfoyle, 'Nuclear and Particle Physics at the University of Richmond', Medium Energy subfield review of the Office of Nuclear Physics Comparative Research Review, Gaithersburg, MD, June 13, 2013.

Service Work

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

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

3. Chair of CLAS Collaboration chair nominating committee.