Continuation Progress Report

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

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Reporting Period: January 1, 2015 to December 31, 2015

Annual Reporting Period

1 Introduction

In this report we describe the progress made during the period January 1, 2015 to December 31, 2015 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 research is part of the electromagnetic nuclear physics program in Hall B at the Thomas Jefferson National Accelerator Facility (JLab) which houses the CLAS12 detector now under construction. In 2015 the group included one faculty member (Gilfoyle) and three undergraduates at the University of Richmond (a primarily undergraduate institution). One of these undergraduates, Keegan Sherman, has applied to Ph.D. programs and wants to pursue his doctorate in nuclear physics. In the past Gilfoyle mentored a masters student from the University of Surrey in the UK through a joint Surrey/Richmond program. We expect another Surrey masters student to join the Richmond group in 2016, but there were no graduate students in the group in 2015. In June 2015, Gilfoyle was elected chair of the CLAS Collaboration for a two-year term that will include first beams in the new CLAS12 detector at JLab. The Collaboration consists of about 220 physicists and is responsible for the construction, commissioning, and operation of the new CLAS12 detector. Gilfoyle is on sabbatical during the 2015-2016 academic year and received University of Richmond support to spend the full academic year at JLab. He will receive release time from the University in the 2016-2017 academic year to support his work as CLAS chair. In this Introduction we outline the Richmond physics program, list recent accomplishments, and discuss the budget. More details on the physics projects and service work are in the later sections.

The Richmond group is currently working on analysis projects described below and software for the simulation, reconstruction, and analysis of data from the new CLAS12 detector in Hall B upon completion of the 12 GeV Upgrade.[2] Gilfoyle is spokesperson and contact person on an experiment to measure the neutron magnetic form factor G_M^n in Hall B entitled *Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium* (JLab experiment E12-07-104) that will run in the first five years after the Upgrade is complete [1, 2]. The experiment received a scientific rating of A$^-$ by PAC35 in 2010 and 30 days of beamtime [3, 4]. Gilfoyle is co-spokesperson on another 12-GeV proposal to measure G_M^n in Hall A entitled *Precision Measurement of the Neutron Magnetic Form Factor Up to $Q^2 = 18.0$ $(GeV/c)^2$ by the Ratio Method* (JLab experiment E12-09-014). He is also co-spokesperson on a 12-GeV proposal entitled *Quark Propagation and Hadron Formation* (JLab experiment E12-06-117) [5, 6]. Current physics projects focus on preparations for E12-07-104 and completion of CLAS12. In the last year we have developed a simulation of the proposed target for the experiment [7], studied the neutron detection efficiency in CLAS12 [8], and wrote controls software for a new target design [9]. During his sabbatical Gilfoyle began writing software to perform track-based alignment of the CLAS12 detector and is part of the team developing reconstruction code for the CLAS12 time-of-flight system. He continues work on analysis of existing CLAS6 data (CLAS6 is the previous detector that occupied Hall B before the 12 GeV Upgrade). 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 [10] from existing CLAS6 data.[3] A draft analysis note has been submitted to an internal Collaboration review.

During the period of this report Gilfoyle was co-author on five refereed articles [11, 12, 13, 14, 15] and was invited to give a talk entitled *Hall B:User Experience and Utilization* during an external review of the JLab software enterprise [16]. He presented a poster on the JLab campaign to measure the electromagnetic form factors of the proton and neutron entitled *Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab*, at EINN15 in Paphos, Cyprus[17]. Last summer three undergraduates, Keegan Sherman, Omair Alam, and David Brakman, worked with Gilfoyle at Richmond and JLab. Mr. Brakman also worked closely with Chris Cueavas (one of the JLab engineering staff) on-site at JLab. Two of these undergraduates were supported by the DOE grant and one was supported by other University of Richmond funds. All three presented their work at the Fall, 2015 meeting of the Division of Nuclear Physics (DNP) of the APS [7, 8, 9].

We anticipate that at the end of the current budget period (May 31, 2016) there will be less than 10% of the budget period funding remaining in the grant.

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

[2] The JLab accelerator energy has been doubled 12 GeV and a new detector in Hall B is under construction, CLAS12.

[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 Richmond group's physics project are focused on preparations for the G_M^n measurement in Hall B (E12-07-104) and the extraction of the fifth structure function from existing CLAS6 data. 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. To measure G_M^n we will use the ratio of quasielastic (QE) $e-n$ to $e-p$ scattering on deuterium which is less vulnerable to uncertainties than previous methods [18].

The student projects done during the period of this report are described here. We have developed a simulation of a unique, dual-cell, target design for E12-07-104 consisting of a liquid deuterium cell (LD_2) and a co-linear liquid hydrogen (LH_2) cell [7]. Figure 1 shows the target in *gemc*, the CLAS12 simulation code. The motivation here is to simultaneously collect production and calibration data under exactly the same running conditions to ensure their consistency. The major limiting factor in the precision of past G_M^n measurements has been the determination of the neutron detection efficiency (NDE). Here we will use the ^{1}H(e, e$'\pi^+$n) reaction as a source of tagged neutrons by first measuring the $e'-\pi^+$ final state, requiring the missing mass to be consistent with a neutron, and predicting the location of that neutron in CLAS12. The second step is to then search for the predicted neutron. The NDE is extracted from the ratio of found to predicted neutrons. The simulation is complete and will be incorporated into the standard *gemc* distribution. We have also begun studying the NDE in CLAS12 [8]. In this case, we start with a simulation of quasi-elastic neutron production from a deuterium target using *gemc* and a local event generator. From the electron information we predict the neutron location in CLAS12 and then search for it in the detector. Our preliminary results show improved neutron detection efficiency in CLAS12 over CLAS6. The analysis was done with the newly developed CLAS12 reconstruction code and served as an early test for the code. We were the first users to run the reconstruction code on a university computing cluster. We have written control and monitoring software for this target in LabView. LabView is a system-design platform and development environment for a visual programming language from National Instruments. Our program will record data from a liquid deuterium target, send data to shift workers, and throw alarms if necessary. A test stand was created to mimic the monitoring system of the cryo-target with sensor data simulated via software-controlled hardware components (voltage sources, resistors, *etc.*). The test stand used a National Instruments NI USB-6351 data acquisition board obtained with grant funds. The program can read, log, and display values and alarms for physical and software channels that simulate data from a real target. This code is complete and consistent with the current stage of the experimental design process.

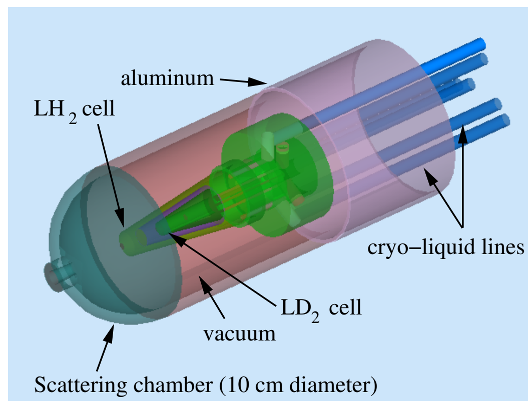

Figure 1: Dual-cell target for Hall B G_M^n experiment in the *gemc* simulation.

The Richmond group is committed to development projects for the JLab 12-GeV Upgrade to enhance the experimental equipment in Hall B [19]. We are responsible for design, prototyping, development, and testing of software for event simulation and reconstruction in CLAS12. Gilfoyle has taken on the task of track-based alignment of the Silicon Vertex Tracker (SVT) in CLAS12. Reaching the CLAS12 design specifications requires understanding the geometry of the detector components as they are built and installed and during their operation. Differences between the nominal geometry and the detector can degrade the resolution, lead to systematic biases in the data, and alter the physics results. Gilfoyle focused on the SVT alignment for his sabbatical after consulting with the JLab staff involved with the SVT reconstruction (V. Ziegler and Y. Gotra). The construction of the SVT is complete and it is undergoing commissioning prior to installation in Hall B. Cosmics rays are being detected in it and we have already used them to measure the misalignment of some of the sensors in the device. The SVT consists of four concentric barrels that form four detecting regions. Each barrel or region consists of modules made of two layers of silicon detectors, each 4.2 cm wide and

41.9 cm long. Each silicon module is identical and different numbers of these modules are used to construct each region with an increasing radius. We have observed misalignments between regions of around 200 μm. To test the validity of this observation and to detect problems in the reconstruction code, we have used the CLAS12 simulation *gemc* to produce Monte Carlo 'cosmic' data. The simulation has 'perfect' geometry and with the reconstruction code we see shifts close to zero with an uncertainty of about 2 μm - well within the design specifications of the SVT. This result shows the shifts observed in the cosmic data are not an artifact of the reconstruction code [20]. Gilfoyle has also begun to study the use of the program `millepede` [21] for track-based alignment using the linear least squares method with a large number of parameters. This could be an important tool since the SVT needs approximately 650 parameters to describe its geometry. The forward time-of-flight system in CLAS12 actually consists of separate, back-to-back, panels of scintillator paddles whose measurements need to be combined into a single result. Gilfoyle works with the team at JLab and Moscow State University on this project. We are studying ways to combine the separate timing signals from the two panels to obtain improved timing resolution in order to enhance the particle identification in CLAS12. The project builds on Gilfoyle's experience in 2013 when he mentored a masters student from the University of Surrey in the UK who wrote the first version of the program [22].

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 [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 $Q^2 = 0.2 - 2.0\ (\mathrm{GeV/c})^2$ 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 [10, 23]. We have submitted a draft analysis note for internal Collaboration review.[4] We have performed a variety of changes and extensions to the analysis in response to the questions raised by the committee. We have revised our comparison of the data with a calculation by W. van Orden. Here, the calculation of the asymmetry A'_{LT} is a function of the missing momentum p_m, 4-momentum transfer Q^2, and Bjorken x_{Bj}. We start with the calculation at a particular value of p_m and construct its $Q^2 - x_{Bj}$ surface. We then weight each point on that surface by the probability distribution extracted from the data. Next, we integrate over all Q^2 and x_{Bj} to obtain the theory calculation at that value of p_m weighted by the CLAS6 acceptance. Our results show moderate differences with our previous results.

Gilfoyle continues to work on software planning for CLAS12. The software effort for the entire Laboratory was assessed in February, 2015 by an external panel and Gilfoyle gave a presentation on the CLAS12 software user environment [24].

3 Professional and CLAS Collaboration Service Work

Gilfoyle was elected chairperson of the CLAS Coordinating Committee (CCC) of the CLAS Collaboration in June 2015 and began his two-year term September 1, 2015. The CCC is the main governing body of the Collaboration. The Collaboration consists of about 220 physicists from 39 institutions in twelve countries and is responsible for the construction, commissioning, and operation of the CLAS12 detector. The Chairperson of the CCC is the collaboration spokesperson and principal contact to the Jefferson Lab directorate for the CLAS Collaboration. The chairperson has responsibility for assuring smooth operation of the Collaboration and organizing the three annual Collaboration meetings [25].

Before becoming CLAS chairperson Gilfoyle was chair of an internal CLAS Collaboration review of a proposal that was being considered for submission to PAC43. He also served on the CLAS Speakers Committee which oversees and archives talks presented by Collaboration members. He gave up that assignment when he became Collaboration chairperson.

[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.

References

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[13] H. S. Jo et al. Cross sections for the exclusive photon electroproduction on the proton and Generalized Parton Distributions. *Phys. Rev. Lett.*, 115(21):212003, 2015.

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[16] G.P. Gilfoyle. Hall B:User Experience and Utilization. Presented at the 12 GeV Software and Computing Review, February 10-11, 2015.

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

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

[25] G.P. Gilfoyle. CLAS Chair Reports. Presented at the CLAS Collaboration Meeting, Oct, 2015.

Summary of Contract-Related Activities

Refereed Publications

1. M. E. McCracken et al. Search for baryon-number and lepton-number violating decays of hyperons using the CLAS detector at Jefferson Laboratory. *Phys. Rev.*, D92(7):072002, 2015.
2. N. Guler et al. Precise determination of the deuteron spin structure at low to moderate Q^2 with CLAS and extraction of the neutron contribution. *Phys. Rev.*, C92(5):055201, 2015.
3. H. S. Jo et al. Cross sections for the exclusive photon electroproduction on the proton and Generalized Parton Distributions. *Phys. Rev. Lett.*, 115(21):212003, 2015.
4. N. Zachariou et al. Determination of the beam-spin asymmetry of deuteron photodisintegration in the energy region $E = 1.1\ 2.3$ GeV. *Phys. Rev.*, C91(5):055202, 2015.
5. S. Pisano et al. Single and double spin asymmetries for deeply virtual Compton scattering measured with CLAS and a longitudinally polarized proton target. *Phys.Rev.*, D91(5):052014, 2015.

Invited Talks

1. G.P. Gilfoyle, 'Hall B: User Experience and Utilization', 12 GeV Software and Computing Review, Jefferson Lab, February, 2015.
2. G.P. Gilfoyle, 'CLAS12 Track-Based Alignment', CLAS12 'First Paper' Workshop, Oct 20, 2015.

Contributed talks and posters.

1. G.P.Gilfoyle, 'Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab', Electromagnetic Interactions in Nucleons and Nuclei 2015, Paphos, Cyprus, Oct 29, 2015, poster.
2. D.Brakman, G.P.Gilfoyle, C.Cuevas, and S.Christo, 'Cryotarget Control Software for Liquid Deuterium', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00039 (2015), poster.
3. O.Alam, G.P.Gilfoyle, and S.Christo, 'Dual Target Design for CLAS12', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00121 (2015), poster.
4. K.Sherman and G.P.Gilfoyle, 'Study of the Neutron Detection Efficiency for the CLAS12 Detector', Bull. Am. Phys. Soc., Fall DNP Meeting, EA.00122 (2015), poster.

5. G.P. Gilfoyle, ‘CLAS Chair Reports’, CLAS Collaboration Meeting, Oct, 2015.

Other Presentations

G.P. Gilfoyle, ‘Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation’, presented at the University of Richmond, January 30, 2015.

Service Work

1. Chair, CLAS Collaboration, elected June, 2015, term began September 1, 2015.
2. Reviewer, CLAS Collaboration.
3. Reviewer, National Science Foundation, Nuclear Physics Program, Physics Division, Directorate for Mathematical and Physical Sciences.