Physics Department, University of Richmond

SUBFIELD: Medium Energy (ME)

CURRENT GROUP MEMBERS:

Faculty (tenured): G.P.Gilfoyle (PI)

Graduate Students: A.Colvill (Joint Richmond/Surrey masters student)

Undergraduate students: K.Sherman, L.Murray, J.Ruger

PHYSICS BEING ADDRESSED/GOALS:

- Measure the elastic magnetic form factor of the neutron G_M^n to unravel the quark and gluon substructure of the nucleon and to rigorously test nuclear models and the predictions of QCD (Jefferson Lab (JLab) experiments E12-07-104 and E12-09-119).
- Extract the fifth structure function of the deuteron from the $^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$ reaction at JLab to test the hadronic model of the nuclear force.
- Investigate quark confinement in nuclei using hadron electroproduction from a range of nuclear targets (JLab experiment E12-06-117).
- Develop software for the calibration, simulation, reconstruction, and analysis of data from the CLAS12 detector now under construction as part of the JLab 12 GeV Upgrade.

ACCOMPLISHMENTS/HIGHLIGHTS (January 1, 2010 - April 30, 2013):

- JLab Experiment E12-07-104 (spokesperson: Gilfoyle) to measure G_M^n with CLAS12 was reviewed by PAC35, received a scientific rating of A^-, and was awarded 30 days of beam time during the first five years of running after the JLab 12 GeV Upgrade.
- JLab Experiment E12-09-019 to measure G_M^n in Hall A received a rating of B^+ from PAC35 and was awarded 25 days of beam time during the first five years of running.
- Submitted a draft technical report of our analysis of the fifth structure function of the deuteron for internal CLAS Collaboration review.
- Published a study of the electroproduction of hadrons that may form Bose-Einstein Correlations in the proposed Electron-Ion Collider (arXiv:1108.1713v2 [nucl-th]).
- Developed a simulation of the CLAS12 electromagnetic calorimeter (CLAS-NOTE 2011-019) and studied the simulated neutron detection efficiency in the CLAS12 forward time-of-flight (FTOF) counters (CLAS-NOTE 2011-015).
- Received funding from DOE to support a masters student who is writing the CLAS12 FTOF reconstruction software (Alex Colvill, University of Surrey).
- Constructed a computing cluster at Richmond with NSF MRI funding; used for development and testing of service-oriented software for CLAS12 reconstruction code.

FUNDING SUPPORT LEVEL BY NP FOR FY10-12 ($K):

	FY10	**FY11**	**FY12**
Total Salaries, Wages and Fringe Benefits	$25	$26	$27
Permanent Equipment			
Travel	$6	$6	$3
Other Direct Costs	$2	$2	$2
Total Direct Costs	$33	$34	$32
Indirect Costs	$13	$14	$14
Total Budget	$46	$48	$46

The Nuclear and Particle Physics Group at the University of Richmond consists of one faculty member (Gilfoyle), one masters student (Colvill) in a joint program with the University of Surrey, and 2-4 undergraduates. Richmond is a primarily undergraduate institution (there are no graduate programs in Physics) with about 3,000 students. Typical teaching loads are five courses/year. The scientific motivation is focused on three areas: (1) hadron structure and its emergence from Quantum Chromodynamics (QCD), (2) the transition from a hadronic to a quark-gluon-based description of nuclei, and (3) software development to support the 12 GeV Upgrade at Jefferson Lab (JLab). Most, but not all, of the program is focused on Hall B at JLab. Since January, 2010 Gilfoyle has presented eighteen talks at collaboration meetings, colloquia, *etc* in addition to those in Table 4. The undergraduates have presented six posters at national meetings and nine at local symposia.

Mapping the internal landscape of the nucleon is a fundamental challenge to nuclear physics and central to the future program at JLab. It is a goal of the NSAC Long Range Plan. The Richmond group is part of a broad assault at JLab (six approved experiments for the future 12 GeV Era) to measure the elastic electromagnetic form factors (EEFFs); essential observables that encode the distribution of charge and magnetization within the nucleon. There are four EEFFs (electric and magnetic ones for the proton and neutron) and we are focused on the magnetic form factor of the neutron G_M^n. Measuring G_M^n will map the distribution of magnetism in the neutron, but it also provides an important constraint on generalized parton distributions (GPDs). GPDs hold the promise of building a new, richer, tomographic image of the nucleon. The G_M^n measurement will, when combined with the other EEFFs, challenge lattice QCD. In particular, the isovector combination of the EEFFs is free of computationally-demanding, disconnected diagrams and it is an early challenge for lattice QCD. These measurements also create the chance to map the quark and gluon distributions of the nucleon. Gilfoyle is spokesperson and contact person for JLab Experiment E12-07-104 in Hall B and is a collaboration member of JLab Experiment E12-09-119 in Hall A.

We will investigate hadron confinement that emerges from QCD by studying the space-time structure of quarks traveling through cold nuclear matter and using the nucleus as a filter. After being struck by a virtual photon, a quark propagates across the nucleus and we measure the attenuation of the final hadrons and their transverse momenta to extract the quark production times (*i.e.*, the lifetime of a bare, struck quark) and the hadron formation times (*i.e.* the time for a hadron to become fully dressed with its gluon field). Gilfoyle is a collaborator on JLab Experiment E12-06-117 in Hall B.

The second component of the Richmond program is unraveling the transition from the hadronic model of nuclear physics to a quark-gluon one. We are studying the importance of final-state interactions (FSI), relativistic corrections, meson-exchange currents, and isobar configurations in the GeV region to establish a hadronic baseline. This baseline will enable us to more clearly see the geography of the transition. We use the deuteron as a laboratory for the $N-N$ force and have measured its little-known fifth structure function. This part of the deuteron response is non-vanishing only out of the scattering plane formed by the incoming and outgoing electron. It is sensitive to FSI and can be used to distinguish among different components of the $N-N$ force, *e.g.* spin-flip versus double spin-flip.

The final leg of the Richmond program is a technical one, software development for the JLab 12 GeV Upgrade. The new detector being built in Hall B, CLAS12, will operate at ten times the luminosity of the previous detector (CLAS6). The Laboratory has challenged

the CLAS Collaboration to have software working and in place on the first day of operations to calibrate, reconstruct, and analyze the new data and to keep pace with the high rates. We are developing new software tools like service-oriented architecture and exploring new technologies like Intel Corporation's Many Integrated Cores (MICs) that will enable us to keep pace with the data flow.

We now discuss the progress in each of the areas described above over the last three years. In the hadron structure component of the program, the proposed experiment to measure G_M^n in Hall B has been developed further. We use the ratio of quasielastic en/ep events from electron scattering on a deuterium target and additional EEFF information to extract G_M^n. CLAS12 has two systems, the electromagnetic calorimeter (EC) and the forward, time-of-flight (FTOF) system that will be used to detect neutrons; providing a powerful consistency check on our results. A similar method was used in a CLAS6 experiment by the E5 group (Gilfoyle is a member).[1] Our JLab proposal (E12-07-104) was originally approved in 2007. In January, 2010 an update was submitted at the request of JLab PAC35. Gilfoyle presented the update. The experiment received an A^- rating and was awarded 30 days of beam time during the first five years of running after the 12 GeV Upgrade is complete. We have also joined a collaboration in Hall A to make a similar measurement of G_M^n that will use the same ratio method on deuterium, but with different spectrometers and a different technique to measure the neutron detection efficiency. The PAC35 report states the two measurements will 'allow a better control for the systematic error', gave a scientific rating of B^+ to the Hall A experiment, and allocated 25 days of beamtime. Finally, the approved hadron attenuation experiment, E12-06-117, was reviewed in August, 2010 by JLab PAC36, received an A^- rating, and was awarded 60 days of beamtime.

We are making preparations for the G_M^n measurement in Hall B (E12-07-104) on several fronts. To test the CLAS12, Geant4-based, simulation package (called *gemc*) we generated Monte Carlo neutron events and extracted the neutron detection efficiency (NDE) of the forward time-of-flight (FTOF) detectors in CLAS12. These detectors will be re-used from CLAS6 so the simulated NDE should agree with past measurements. Using some of the same techniques to analyze the simulation that will be used in the G_M^n measurement we obtained excellent agreement between the simulation and the measured CLAS6 results (CLAS-NOTE 2011-015). The EC will also be re-used from CLAS6 in the new CLAS12 and we will use this device to detect neutrons (in addition to the FTOF). We implemented the EC in *gemc*, performed a series of tests of the performance of the simulation, and obtained good agreement with previous simulations of the EC for CLAS6 (CLAS-NOTE 2011-019). We have developed a Geant4-based simulation of the core components of the G_M^n target in *gemc* to study the design for the target. More recently, our masters student (Colvill) has written the third generation reconstruction code for the FTOF in CLAS12.

We have been analyzing existing data from the CLAS6 E5 run period to extract G_M^n. These data consist of three sets of run conditions and results from two of those sets have been published.[2] Our goal here is to complete the analysis of the third data set using the same techniques we plan to use in CLAS12 G_M^n experiment.

We have also studied simulations of correlations between bosons (*e.g.* $\pi^+\pi^+$) to explore

[1] Lachniet, A. Afanasev, H. Arenhövel, W. K. Brooks, G. P. Gilfoyle, D. Higinbotham, S. Jeschonnek, B. Quinn, M. F. Vineyard, et al. *Phys. Rev. Lett.*, 102(19):192001, 2009.

[2] *Ibid.*

the space-time extent of the source and learn about the dynamics of its formation. These Bose-Einstein Correlations occur when particles form near one another so their wave functions interfere. This work was done at the kinematics of the proposed Electron-Ion Collider, but uses techniques relevant to the hadron attenuation experiment (E12-06-117).

For the second part of the Richmond program we are analyzing the $^2\mathrm{H}(\vec{e}, e'p)n$ reaction to extract the fifth structure function. The work is far along. Our results show significant helicity asymmetries that are only partially reproduced by theory. We have presented the results at Collaboration meetings and submitted a draft of an analysis note for internal, CLAS Collaboration review. This is the first step in approving the results for publication.

Software development for CLAS12 is the third component of the Richmond program. We have already mentioned some of our accomplishments above. We focus many of our efforts in software on projects that will prepare us for the G_M^n measurement in Hall B and at the same time contribute to the CLAS12 software program. The recent work on the FTOF reconstruction will be used in future simulations of the neutron detection and will also be part of the upcoming 'stress test' of the CLAS12 reconstruction software. We have taken leadership roles in the software planning process. Gilfoyle gave the CLAS12 software presentation at an internal, JLab review of software preparations for the 12 GeV Era in 2011 and estimated the hardware requirements for CLAS12 as part of an external review of the computing enterprise at JLab in 2012. He organized a software workshop attended by about fifty Collaboration members at the University of Richmond in May, 2010. We have also completed development of a computing cluster at the University of Richmond using a Major Research Instrumentation grant from NSF awarded in 2009. The Richmond cluster has been the test bench for developing a service-oriented architecture for the CLAS12 software.[3]

Undergraduates have contributed to all the projects described here. Since January, 2010 they have presented six posters at national meetings and nine at local symposia. Two are working towards doctorates in nuclear physics, one in applied mathematics, and one in electrical engineering. Two of these students are women. CLAS Collaboration rules prevent undergraduate workers from appearing on CLAS publications. The University of Richmond has provided stipends for one undergraduate student each summer since 2010 (two more are supported each summer from the DOE grant) and funding for travel by the PI to JLab.

We now discuss our plans for the next 1-2 years. Most of our effort will be focused on CLAS12 software development and the program in hadronic structure. We are preparing for the G_M^n measurement in Hall B. Hall B commissioning is expected to begin in the third quarter of FY15 and the software has to be ready. We will continue development of the FTOF reconstruction package to take advantage of a new, more-highly-segmented panel of scintillators that will be located in front of (and closer to the target) the panel made from scintillators re-used from CLAS6. We will begin studying the attributes of the G_M^n target in simulation and likely start working with the Hall B technical staff to design the target. We have also begun to investigate new computing technologies (Many Integrated Cores (MICs) and graphical processing units (GPUs)) to speed the reconstruction and simulation of the CLAS12 data. We will, as resources permit, continue analysis of the E5 data to extract G_M^n from the unpublished portion of the data set. The other focus over the next two years will be to finish the analysis of the fifth structure of the deuteron now under Collaboration review.

[3]V. Gyurjyan, D. Abbott, G.P. Gilfoyle, J. Carbonneau, G. Heyes, S. Paul, C. Timmer, D. Weygand, and E. Wolin. *J. Phys. Conf. Ser.* 331 (2011) 032013.

TABLE 1: DISTRIBUTION OF RESEARCH EFFORT (FRACTIONAL FTE) AMONG GROUP'S ACTIVITIES:

Subfield: Medium energy (ME)

	Nucleon structure /spin physics	**PVES***	**Hadron spec-troscopy**	**SM** tests/ BSM*** search**	**Other within ME**	**Other subfields in NP**	**Other non-NP effort**	**Total FTE (sum=1)**
Faculty G.P.Gilfoyle	0.55	0.0	0.0	0.0	0.05 **Hadrons and Cold Nuclear Matter**	0.0	0.4 teaching, university service	1.0
Grad. students A.Colvill	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
Total	1.55	0.0	0.0	0.0	0.05	0.0	0.4	2.0

*PVES: Parity violating electron scattering **SM: Standard Model ***BSM: Beyond Standard Model

GRADUATE STUDENT AND POST-DOC TRACKING INFORMATION

TABLE 2: GRADUATE STUDENT TRACKING INFORMATION (Fall 2008 - Spring 2013)

Grad Student Name	**Advisor**	**Date Joined the Group**	**Actual or expected graduation date**	**Degree awarded/ expected (MS/PhD)**	**Present Institution**	**Present Position**
A.Colvill	G.P.Gilfoyle	Spring, 2013	(Spring, 2014)	(MS)	University of Surrey	

TABLE 3: POSTDOCTORAL TRACKING INFORMATION (Fall 2008 - Spring 2013)

Post-Doc Name	**Advisor**	**Beginning Date**	**End Date**	**Present Institution**	**Present Position**
None					

GROUP BIBLIOGRAPHY (January 1, 2010 - April 30, 2013)

Prominent Refereed Publications

1. H. Egiyan et al. CLAS Collaboration, "Upper limits for the photoproduction cross section for the $\Phi^{--}(1860)$ pentaquark state off the deuteron", Phys. Rev. C85 (2012) 015205.

2. V. Gyurjyan, D. Abbott, J. Carbonneau,* G. Gilfoyle, D. Heddle, G. Heyes, S. Paul, C. Timmer, D. Weygand, E. Wolin, "CLARA: A contemporary approach to physics data processing", J. Phys. Conf. Ser. 331 (2011) 032013.

3. A. Daniel et al. CLAS Collaboration, "Measurement of the nuclear multiplicity ratio for K_s^0 hadronization at CLAS", Phys.Lett. B706 (2011) 26-31.

*University of Richmond undergraduate.

Invited Talks/Proceedings

1. G. P. Gilfoyle, "Few-body physics with CLAS", Few Body Syst. 50 (2011) 15-22.

2. G. P. Gilfoyle, "Future Measurements of Elastic Electromagnetic Form Factors at Jefferson Lab", presented at PINAN11 in Marrakech, Morocco September 26, 2011.

3. G. P. Gilfoyle, "Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium", JLAB-PHY-10-1217, Proceedings of Exclusive Reactions at High Momentum Transfer IV (2011).

4. D.Boer et al. "Gluons and the quark sea at high energies: distributions, polarization, tomography", arXiv:1108.1713v2 [nucl-th].

5. G. P. Gilfoyle, "Update for E12-07-104: Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on Deuterium", presented at Jefferson Laboratory PAC35, January, 2010.

Table 4: Summary of Publications

Period: January 1, 2010 - April 30, 2013

Name	**Letter Publications**	**Other Refereed Journals**	**Invited Talks**
Faculty G.P.Gilfoyle	9(1)	12(2)	5
Grad Students A.Colvill			
Total	9(1)	12(2)	5

Biographical Sketch

GERARD GILFOYLE (PI)

Degrees	Ph.D., University of Pennsylvania, 1985 - H.T. Fortune, adviser. A.B., cum laude, Franklin and Marshall College, 1979.
Experience	1987-present - Assistant, Associate, Full Professor, University of Richmond. 1994-1995, 2002-2003, 2009-2010 - Scientific Consultant, Jefferson Laboratory. 1999-2000 - AAAS Defense Policy Fellow. 1985-1987 - Postdoctoral Research Fellow, SUNY at Stony Brook.
Research Grants	2001-2002, 2010-2012 - NSF MRI grants ($175,000, $162,000). 1990-present - US Department of Energy ($1,560,000). 2010 - CLAS12 Software Workshop, JSA/SURA Initiatives Fund ($7,500). 1994-1995, 2002-2003, 2009-2010 - JSA/SURA, JLab sabbatical support.
Selected Service	2006 - 2010 - Chair, CLAS Collaboration Nuclear Physics Working Group. 2000 - present - Reviewer, DOE, NSF, SURA, DOD, CLAS Collaboration. 2000 - 2006 - Chair, Department of Physics, University of Richmond.
Honors	2008-present - Clarence E. Denoon Professor of Science, University of Richmond. 2003 - University of Richmond Distinguished Educator Award.