Dean of the School of Arts and Sciences  
University of Richmond  
28 Westhampton Way  
Richmond, VA 23173

Dear Dean Newcomb:

Please find enclosed my application for a full-year, enhanced-salary sabbatical leave for the 2009-2010 academic year. This document contains the six items listed under the application procedures of the instructions for applying for the enhanced-salary sabbatical leave. Page 1 of the application immediately following this cover letter lists those six items and where they can be found in the document. You should receive three letters from the external reviewers that evaluated this proposal. If you don’t receive those letters soon, let me know so I can expedite the process. If you have any questions, please let me know.

Sincerely,

Dr. Gerard P. Gilfoyle  
Department of Physics
Enhanced Sabbatical Proposal

Dr. Gerard P. Gilfoyle

Physics Department, University of Richmond

1. I am applying for a full-year, enhanced sabbatical for the 2009-2010 academic year. This year long sabbatical is contingent on funding from the University or one of the other sources listed below. If I do not receive funding, then I would prefer to be on leave during the fall, 2009 semester.

2. I will be applying to the following sources for funding the full-year sabbatical.

   - Program funded by the Southeastern Universities Research Association (SURA) and JSA to support faculty from SURA institutions to do research at JLab.
   - I will request half of my academic year salary.
   - Application date: January 25, 2009.
   - I expect to hear about this support by mid-April, 2009.

(b) Thomas Jefferson National Accelerator Facility
   - Program funded by JLab to support faculty doing research at JLab.
   - I will request half of my academic year salary.
   - Application date: January 25, 2009.
   - I expect to hear about this support by mid-May, 2009.

(c) US Department of Energy (DOE)
   - Intermediate-Energy program in the DOE Office of Science supports research at JLab.
   - I requested travel support for my sabbatical.
   - Application date: December 1, 2008.
   - I expect to hear about this support by mid-April, 2009.

3. External referees.

Dr. Richard G. Milner
- Position - Professor of Physics and former Director, Laboratory for Nuclear Science, MIT.
- Curriculum Vitae - Not available; see page 3 for a short biographical sketch and a listing of his publications.
- Expertise - Experimental nuclear physicist and former director of a major US accelerator center at MIT that investigates similar physics questions to the ones studied at JLab.
- Relationship - I have met him at conferences, but we have not worked together.

Dr. Gerald Miller
- Position - Professor, Department of Physics, University of Washington, Seattle.
- Curriculum Vitae - See page 9.
- Expertise - Theoretical physicist with expertise in intermediate energy nuclear physics like that performed at JLab; Principal investigator, ‘Theoretical Nuclear Physics’ Department of Energy grant DE-FG03-97ER41014.
- Relationship - I know him professionally, but have not worked with him on any projects.
Dr. Will Brooks

- Position - Professor and Experimental Nuclear and Particle Physics Group Leader, Department of Physics, Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile.
- Curriculum Vitae - See page 26.
- Expertise - Experimental physicist and former staff scientist at JLab; E5 group leader for the measurement of the neutron magnetic form factor that I am now leading.
- Relationship - He was group leader for the physics projects that I have been focused for the last few years. He is intimately aware of my contribution to the analysis of the magnetic form factor of the neutron and the structure functions of the neutron that are described in this proposal.


5. Representative grant proposals - I have included my DOE grant renewal proposal with a request for sabbatical travel funds and other items. See attached document on page 42.

6. Updated CV - See page 81.
Biographical Sketch

Richard G. Milner

Research Interests

Professor Milner is the former Director of MIT’s Laboratory for Nuclear Science (LNS), and a member of its Medium Energy Physics Group. His research is focused on studying the spin structure of strongly interacting systems. A major focus of his research effort over the last decade has been the HERMES experiment to study the spin structure of the nucleon. This work was carried out in collaboration with Prof. Robert P. Redwine. HERMES has provided important new data on the flavor decomposition of the quark spin and on the contribution of the glue, yielding a number of new, unexpected results.

One of Prof. Milner’s most recent efforts was at the MIT Bates Linear Accelerator Center, where the construction of a new large detector called the “Bates Large Acceptance Spectrometer Toroid” (BLAST) was completed. This work was carried out in collaboration with Profs. Bill Bertozzi, Haiyan Gao, June Matthews, and Bob Redwine. BLAST is used with the stored polarized beam to measure spin-dependent electron scattering from polarized hydrogen, deuterium and He-3 targets. BLAST provides important information on the spin structure of light nuclei as well as on the neutron form-factors.

Career Summary

Professor Richard Milner joined the MIT faculty in 1988, where he served as Director of the Bates Linear Accelerator Center, and later as Director of MIT’s Laboratory for Nuclear Science. He received his B.Sc. in 1978 and his M.Sc. in 1979 in Physics from the University College, Cork, Ireland, and his Ph.D., also in Physics, in 1984 from the California Institute of Technology, where he was a Research Fellow from 1985 to 1988.

* From the MIT website (http://web.mit.edu/physics/facultyandstaff/faculty/richard_milner.html).

Publication List from the SPIRES database at Stanford


10. “Measurements of electron proton elastic cross sections for $0.4-$(GeV/c)$^2 < Q^2 < 5.5-$(GeV/c)$^2$”, M. E. Christy et al. [E94110 Collaboration], Phys. Rev. C 70, 015206 (2004) [arXiv:nucl-ex/0401030]


15. “Asymmetry measurements from a polarized He-3 target”, D. W. Higinbotham et al., Prepared for 12th International Symposium on High-energy Spin Physics (SPIN 96), Amsterdam, Netherlands, 10-14 Sep 1996


27. “Cryogenic polarized internal He-3 gas target for HERMES”, S. F. Pate et al., Prepared for 5th International Workshop on Polarized Beams and Polarized Gas Targets, Cologne, Germany, 6-9 Jun 1995


37. “Color transparency in (e,e’ p) experiments”, R. G. Milner [NE18 Collaboration], Prepared for 6th Workshop on Perspectives in Nuclear Physics at Intermediate Energies, Trieste, Italy, 3-7 May 1993


41. “Measurement Of The Spin Structure Of The Nucleon At Hera”, R. G. Milner, Prepared for BNL Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities, Upton, NY, 4-6 Mar 1993


CURRICULUM VITAE

Name: Gerald Alan Miller
Office Phone: 206-543-2995

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University of Washington
Seattle, Washington 98195

Home Phone: 206-523-8518
Marital Status: Married, two children

Date and Place of birth: March 20, 1947, New York City

Education:

- Bronx High School of Science 1963
- City College of New York 1967
- Massachusetts Institute of Technology, M.S. 1968
- Massachusetts Institute of Technology, Ph.D. 1972

Employment:

- University of Washington, Seattle, Washington 98195
  - 1985 - present Professor
  - 1980 - 1985 Associate Professor
  - 1975 - 1980 Research Assistant Professor
- Jefferson Laboratory
  - 2000-2003 Program Advisory Committee
- Jefferson Laboratory
  - 2004 Visiting Theorist
- Lawrence Berkeley Laboratory
  - 2004 Visiting Theorist
- Brookhaven National Laboratory
  - 2004 Visiting Theorist
- ECT*, Trento
  - 2003 Visiting Theorist
- CSSM, Adelaide, Au.
  - 2003 Visiting Theorist
- Stanford Linear Accelerator Center
  - 1997 Visiting Theorist
- TRIUMF
  - 1988 - 1989 Visiting Staff Member
- University of Illinois
  - 1989 Visiting Research Professor
- CERN, Geneva, Switzerland
  - 1982 - 1983 Paid Scientific Associate
- Los Alamos National Laboratory
- Carnegie-Mellon University
  - 1972 - 1975 Research Physicist
Honors and Awards:

New York Regents Scholarship, New York College Teaching Fellowship
Dean’s List, Magna Cum Laude, Phi Beta Kappa, Sigma Xi
Graduate Fellowship at MIT
Fellow, American Physical Society
Fellow, American Association for the Advancement of Science

Outside Professional Positions:

Program Advisory Committee, Los Alamos National Laboratory, 1979-1982
Editorial Board Member, Physical Review C, 1986-1988
Program Committee, DNP, American Physical Society, 1985-1987
Member, APS Task Force to review Reviews of Modern Physics, 1992-1993
Lead organizer, national Institute for Nuclear Theory programs, 1990-92;
1994 (workshop); 1996; 1998 (2 mini-workshops); 2001, 2004 (workshop)
National Science Foundation, Nuclear Theory panel member, 1997, 2003
Physics Today, panel member for book reviews, 1997-2002
Program Advisory Committee member for Jefferson Laboratory 2000-2003
Managing Editor, International Journal Modern Physics E, 2004
USA Correspondent for Nuclear Physics News International, 2004


Publications–Refereed Journals


Publications–Refereed Journals


Publications–Refereed Journals


177. “Charge symmetry violation in $pn \rightarrow d\pi^0$ as a test of chiral effective field theory,” Phys. Lett. B493, 65 (2000) ; (with U. van Kolck and J. A. Niskanen)


201. “Observation of the charge symmetry breaking $d+d \rightarrow ^4He+\pi^0$ reaction near threshold,” Phys. Rev. Lett. 91, 142302 (2003), with E. J. Stephenson et al.


204. “Chiral solitons in nuclei: Saturation, EMC effect and Drell-Yan experiments” Phys. Rev. Lett. 91 212301-1 (2003), with J. R. Smith

205. “Survey of Charge Symmetry Breaking Operators For $dd \rightarrow \alpha\pi^0$,”, Phys. Rev. C 69, 044606 (2004), with A. Gardestig et al.


Publications–Refereed Journals


William K. Brooks

Personal Data
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Email: brooksw@jlab.org or william.brooks@usm.cl
Date of birth: March 07, 1959
Passport: 20739039-7
Chilean RUT number: 22.647.144-8

Education
Ph.D., September 1988, Physics, Duke University, Durham North Carolina.

Employment History
January 2008 - Present
Professor
Experimental Group Leader, High Energy Physics
Universidad Técnica Federico Santa María

May 2005 to November 2007
Senior Staff Scientist
12 GeV Associate Project Manager for Physics
Thomas Jefferson National Accelerator Facility

October 2003 to April 2005
Staff Scientist III
Hall B Physicist
Thomas Jefferson National Accelerator Facility

October 1995 to September 2003
Staff Scientist II
Hall B Physicist
Thomas Jefferson National Accelerator Facility

January 1993 to September 1995
Staff Scientist I
Hall B Physicist
Thomas Jefferson National Accelerator Facility

November 1990 to December 1992
Research Associate
University of Pittsburgh
September 1988 to November 1989  
*Postdoctoral Researcher*

The Ohio State University

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**Honorary Academic Appointments**

December 2005 to present  
*Jefferson Lab Professor of Physics*

Old Dominion University

PhD Students:


Maryam Motabbed, Florida International University (Brian Raue, University Advisor), Topic will be two-photon exchange measured through electron-proton and positron-proton elastic scattering, anticipated in early 2009.

Taya Mineeva, University of Connecticut (Kyungseon Joo, University Advisor), Topic will be hadron attenuation and transverse momentum broadening for $\pi^0$ mesons in nuclear deep inelastic scattering, anticipated for summer 2011.

**Research Interests**

*A spokesperson for five Jefferson Lab experiments:*

**E-94-117** “The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasi-elastic Electron-Neutron to Electron-Proton Scattering in Deuterium”

**E-02-104** “Quark Propagation through Cold QCD Matter”

**E-04-116** “Beyond the Born Approximation: A Precise Comparison of Positron-Proton and Electron-Proton Elastic Scattering in CLAS”

**E-12-06-117** “Quark Propagation and Hadron Formation”

**E-12-07-104** “Measurement of the Neutron Magnetic Form Factor at High $Q^2$ Using the Ratio Method on Deuterium”
Invited Talks


"Parton propagation and hadron formation in the space-time domain," Sixth International Conference on Perspectives in Hadronic Physics, ICTP, Trieste, Italy, May 2008

"Parton propagation and hadron formation in the space-time domain," UTFSM Seminar, Valparaíso, Chile, March 2008


“Quark Propagation, the Strong Force, and the Mystery of QCD Confinement,” Old Dominion University Physics Department Colloquium, Norfolk, Virginia, November 2005.


**Publications**

For CLAS collaboration papers, the names of ~160 collaboration members are here omitted for brevity.


Electroproduction of phi(1020) mesons at 1.4 < Q**2 < 3.8 GeV**2 measured with the CLAS spectrometer, J. P. Santoro, ..., W. K. Brooks, ... (The CLAS Collaboration), Phys. Rev. C **78**:025210 (2008).


Polarized Structure Function g1LT for p(pol(e),e'K+)+ in the Nucleon Resonance Region, R. Nasseripour, ..., W. K. Brooks, ... (The CLAS Collaboration), Phys. Rev. C **77**:065208 (2008).


“Observation of a backward peak in the γd→π°d cross section near the eta threshold,” Y. Ilieva, ...


“Complete Measurement of Three-Body Photodisintegration of 3He for Photon Energies between 0.35 and 1.55 GeV,” S. Niccolai, …, W. K. Brooks, …, (The CLAS Collaboration).


Other

1 Introduction

This document is a research proposal for a full-year sabbatical at the University of Richmond. The research proposed here builds on the successful program I have developed in electro-nuclear physics at the Thomas Jefferson National Accelerator Facility (Jefferson Lab or JLab) in Newport News, VA that is externally supported by the US Department of Energy and has involved many University of Richmond undergraduates in frontier research at a world-class facility. The primary scientific instruments at Jefferson Lab are a large, one-mile-around, electron accelerator and three large particle detectors or end stations which capture and measure the debris from collisions of the electron beam with nuclear targets. The projects discussed below include an investigation into the fundamental nature of matter and an instrumentation project that are both part of the long-range plan for nuclear physics in the US [1].

The main focus of the research is two-fold. (1) The magnetic form factor of the neutron is a fundamental quantity related to the distribution of electric charges and electric currents within the atomic nucleus. To understand the interior landscape of matter we must know where the electric charge is located! The first project will complete the analysis of a large data set that uses a unique experimental technique to measure the neutron magnetic form factor in a region where there are conflicting measurements from other laboratories. This project will make an important contribution to our understanding of the nucleus and will be the subject of one or more refereed publications. (2) The highest priority in nuclear physics is the upgrade of Jefferson Lab to open new windows into the structure of matter. This undertaking will require the efforts of hundreds of physicists, engineers, and technicians over the next six years. I am the leader of one of the experiments slated to be performed in the first years of running after the upgrade is complete. In preparation for that experiment and as part of the effort to build the new particle detectors at Jefferson lab, I will be developing simulations of neutrons that are important for design and construction of the detectors and for the planning of future experiments. This last project will advance the upgrade of Jefferson and will be the subject of at least one publication, several technical reports, and will provide strong justification for future funding.

I am planning on spending the full academic year on sabbatical (2009-2010) and I am pursuing funding from the US Department of Energy, Jefferson Science Associates, and other sources. I also plan to apply for an enhanced sabbatical from the University.

2 The Quest for Quarks

Nobody has ever seen a quark. Yet, physicists have no doubt about their existence and the central role they play at the very heart of all the matter in the world around us. Figure 1 shows the current, over-simplified, picture of the structure of matter. Within the atomic nucleus lie protons and neutrons (collectively called nucleons) that are in turn composed of three smaller particles; the quarks. Other particles, the gluons, pop in and out of existence in a bubbling soup inside the nucleus and, strangely enough, create the forces that hold the quarks together. It is this force that poses one of the great challenges to our understanding of the Universe. Every other fundamental force we observe gets weaker as two particles get farther apart. This feature is what allows us to launch spacecraft to other planets and to generate electricity. The force that binds quarks or a quark and a gluon together is different. It is constant regardless of the distance between the quarks and gluons. Pull two quarks a meter apart and the force is the same as when they are 100,000 times closer. This ‘confinement’ means that we will never ‘see’ a bare quark.
This is not the whole story. The best theory of the quark-quark force we have now is called quantum chromo-dynamics (QCD). QCD is built on observations made at very high energy where the environment is simpler and easier to understand, but where the conditions are different from the ones inside the nucleus. One of the main reasons for upgrading JLab is to understand the nature of confinement and how quarks combine to form protons and neutrons (the basic constituents of everyday matter). We need to map out the features of the quarks as they go about their everyday lives inside the nucleus. A vital step in this nuclear cartography is to know where the electric charges located within the nucleus and its constituents.

In this Proposal I will describe two physics projects, but first let me describe how one takes data at JLab to set the stage for the description of the research projects. The JLab accelerator produces a electron beam by pushing the electrons through the mile-long, racetrack-shaped, machine up to five times (see Figure 2). This beam is extracted and sent into one of three experimental halls. It is in the halls where the action takes place. The electron beam strikes a nuclear target and a spray of debris is produced that we detect and measure. The detector I use is called the CEBAF Large Acceptance Spectrometer or CLAS (CEBAF stands for the Continuous Electron Beam Accelerator Facility, the actual electron accelerator). This is a large (about 45 tons), $50-million device that was built by my colleagues and me in the CLAS Collaboration. See Figure 3. The CLAS Collaboration consists of about 300 physicists from all over the world who are responsible for building, maintaining, and operating CLAS. The collision or event that I just described occurs about 2000-3000 times each second and we record a deluge of data; about 1 terabyte (1000 gigabytes) per day. One of these large data sets is the focus of the first project.

3 The Magnetic Form Factor of the Neutron

The magnetic form factor of the neutron (known symbolically at $G_M^n$) is a fundamental observable related to the distribution of electric charge and current within the nucleons and atomic nuclei [2]. If we are to claim we understand the nature of matter we must have a theory which describes the position of the charges and currents inside matter. Quantum chromodynamics is our best and most successful theory of how quarks and gluons interact, but at the energies of the particles inside the neutron the theory is nearly intractable. Fortunately, there is a way forward. Using computational methods on high-speed arrays of computers holds the promise of enabling us to solve QCD at nucleon energies. This technique is called ‘lattice QCD’ because space and time are broken down into discrete pieces and the calculations are performed on this space-time lattice which is an approximation to the nearly continuous form of Nature. Full calculations are beyond currently available computers so we make approximations and apply tests to map out the accessible regions of the lattice. As computers and our knowledge increase in power, we expect over the next decade that calculations of the neutron magnetic form factor and other, related quantities will become important tests for the success or failure of QCD in this energy regime. The magnetic form factor of the neutron is especially important because the lattice QCD calculation is, for technical reasons, simpler and ‘cleaner’ than others so
it will be an important early benchmark to meet. It is also worth mentioning that the measurement of $G^n_M$ is part of the long-range plan for nuclear physics in the United States [1].

The research plan for the measurement of $G^n_M$ will now be described. The data have already been collected for the nuclear reaction $eD \to e'n'p$ where the incidence electron ($e$) strikes a deuterium ($D$) target. The debris from the collision consists of the scattered electron ($e'$), a proton ($p$), and a neutron ($n$). The measurement was done with the CLAS detector and consist of three sets of running conditions. In two of those sets the magnet used to bend the trajectories of the electrons and protons and measure their momenta was operated in its standard mode. The analysis of those data is nearly complete and is near the end of its internal, collaboration review. The results will soon be submitted for publication [3]. They will represent a dramatic improvement in the range and precision over previous measurements. See Figure 4 which shows a commonly used form of $G^n_M$ plotted versus the quantity $Q^2$ which represents the size of the kick we impart to the neutron in the collision with the electron beam. Our results are the red points and the other points represent a sample of the best measurements made from laboratories around the world [2] along with several theoretical curves [32, 5, 6, 7]. In the third set of running conditions we used the CLAS magnet in an uncommon configuration and the analysis of that data requires more work. These unanalyzed data are in a lower energy and momentum regime than the other data, but they overlap with other measurements of $G^n_M$ made at different laboratories around the world. Notice in Figure 4, the scatter of points for $Q^2 < 1 \text{ GeV}^2$. These conflicting measurements have spawned a variety of theoretical models. The experimental situation cries out for resolution and our data can help clarify the situation.

The plan for attacking this problem is the following. We will extract the ratio of the production of neutrons to protons from a deuterium target to extract $G^n_M$ as a function of $Q^2$. This is the same method we used successfully on the data from the other two sets of running conditions. The first step in applying this technique to our data is to calibrate the CLAS response. Some of this work has already been done, but two of the CLAS components (the large-angle calorimeters) still need to be calibrated. This will be done with data from a proton target that was exposed to the electron beam simultaneously with the deuterium target. Once the CLAS is calibrated, we then correct for a variety of effects like the detection efficiencies for protons and neutrons in CLAS and the effect of the internal motion of the neutron in the deuterium target. These corrections require a variety of methods from analysis of the calibration data to simulations of the reactions. Once the ratio of neutron to proton production is extracted and corrected, we must make careful studies of the systematic uncertainties in the measurement. For a complex detector like CLAS this process requires thoughtful analysis of the data and accurate simulations of the CLAS response to separate true physics effects from mere artifacts of the detector. When it is all done, we will publish the results.

4 Upgrading the CLAS Detector

A fundamental challenge for modern nuclear physics is to understand the structure and interactions of nucleons and nuclei in terms of QCD. Jefferson Lab’s unique Continuous Electron Beam Accelerator Facility has given the United States leadership in addressing this challenge. The US Department of Energy has begun an upgrade of Jefferson Lab that will double the energy of the JLAB accelerator will enable three-
dimensional imaging of the nucleon, revealing hidden aspects of its internal dynamics. It will complete our understanding of the transition between the hadronic and quark/gluon descriptions of nuclei, and test definitively the existence of exotic hadrons, long-predicted by QCD as arising from quark confinement.

To take full advantage of the new physics opportunities a new CLAS12 detector will evolve from the existing CLAS to meet the basic requirements for the study of the structure of nucleons and nuclei after the CEBAF energy upgrade to 12 GeV. See Figure 5 which shows a conceptual design of the new device. The height of the detector in the figure is about 10 meters.

There are several important questions we seek to answer. A major focus of CLAS12 will be mapping out the three-dimensional structure of the nucleon for the first time. The project is technically challenging and require the high beam currents and wide angular coverage of CLAS12. We still do not understand the source of nucleon spin. Measurements show that the quarks supply only about one-third of the total spin of the proton and our inability to understand this basic property has spawned the ‘spin crisis’. Studies of the nucleon spin structure will also require high beam currents and the unique properties of CLAS12. At the higher energies, new requirements on particle identification make improvements in a wide variety of the technical properties of CLAS12 over CLAS essential for success.

In the summer of 2007, A proposal to extend the measurements of the neutron magnetic form factor to higher energy using the upgraded CEBAF and CLAS12 was approved by the JLab Program Advisory Committee. The new experiment is expected to run during the first five years of operation after the upgrade is complete. During the period of this sabbatical we will begin work on the simulation of events in the CLAS12 to further develop this proposal and others and to contribute to the design and implementation of the components of CLAS12. We are committed to development projects for the JLab 12-GeV Upgrade and will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction. The improved CLAS12 detector will have prodigious software requirements. The online data rate is expected to be 20 kHz with a 10 kByte event size and less than 15% deadtime [8]. We will collect about 1 petabyte of data each year.

Event simulation is an essential aspect of the design of CLAS12 and eventual precision of the detector. For many experiments, the quality of the results will be limited by systematic uncertainties instead of statistical ones. Accurate, precise calculations of the CLAS12 acceptance and response are important to keep those systematic uncertainties small. To do that we expect to generate about four times as much simulated, Monte Carlo data as CLAS12 collects. The CLAS12 simulation will produce data more slowly than the detector itself so the contribution of university groups to this effort is essential. The current CLAS detector takes data at a rate of about 3 kHz. Events can be simulated at a far slower rate; about 2-3 Hz depending on the CPU speed. We expect a similar difference with CLAS12. The same issues that arise in designing the physics experiments also arise in the design and prototyping phase of the project we are just entering. First beams are not expected until the next decade, but this work has already begun. The work described here will be the subject of JLab reports and refereed instrumentation publications.

References


US Department of Energy Renewal Proposal

Medium Energy Nuclear Physics Research at the University of Richmond

G. P. Gilfoyle
Physics Department, University of Richmond
28 Westhampton Way, Richmond, VA 23221
phone: 804-289-8255, email: ggilfoyl@richmond.edu

Grant Contract Number DE-FG02-96ER40980
Grant Period: June 1, 2009 - May 31, 2012

Office of Nuclear Physics: Medium Energy Nuclear Physics Program
Program Manager: Dr. Brad Tippens
Medium Energy Nuclear Physics Research at the
University of Richmond

G. P. Gilfoyle
Physics Department
University of Richmond

Abstract

The nuclear physics program at the University of Richmond is focused on the structure of nucleons and the transition from the hadronic picture of matter to a quark-gluon description. We use the Thomas Jefferson National Accelerator Facility (JLab) to measure the charge and magnetization distributions of the neutron and extract components of the deuteron wave function. We propose a new program to produce strange quarks in the nucleus to study the color force via the hyperon-nucleon interaction. We will push some of these measurements to higher energy as part of the JLab 12-GeV Upgrade.

5 Project Introduction

This is a renewal application to support the University of Richmond electromagnetic nuclear physics research program at the Thomas Jefferson National Accelerator Facility (JLab). Dr. G.P. Gilfoyle is the principle investigator (PI). Our physics projects are listed in Table 1.

<table>
<thead>
<tr>
<th>Title</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of the Neutron Magnetic Form Factor at High $Q^2$ Using the Ratio Method on Deuterium (Gilfoyle: spokesperson and contact person)</td>
<td>E12-07-104</td>
</tr>
<tr>
<td>The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Measurement of the Neutron Magnetic Form Factor at High $Q^2$ Using the Ratio Method on Electron-Neutron to Electron-Proton Scattering in Deuterium</td>
<td>E94-017</td>
</tr>
<tr>
<td>Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)</td>
<td>CLAS-Approved Analysis$^1$</td>
</tr>
<tr>
<td>Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)</td>
<td>E12-06-117</td>
</tr>
<tr>
<td>Spectroscopic Study of Λ Hypernuclei in the Medium-Heavy Mass Region and $p$-Shell Region Using the $(e,e'K^+)$ Reaction (extension of E05-115)</td>
<td>E05-115/E08-002</td>
</tr>
<tr>
<td>Study of Light Hypernuclei by Pionic Decay at JLab</td>
<td>E08-012</td>
</tr>
</tbody>
</table>

Table 1: Summary of physics projects of the Richmond group.

We now summarize our progress in the two years since our last review (2006). We have completed the extraction of the magnetic form factor of the neutron $G_M^n$ for two out of three data sets from the E5 running period at JLab (Section 6.1.1). We took over the completion of this project in spring 2008 after the primary researcher (Lachniet) took a job in industry and we finished the analysis to complete the internal, CLAS Collaboration technical review. The CLAS Analysis Note was approved October 1, 2008 [1]. We are leading the effort to publish a paper on this work. A draft has has been approved by an internal CLAS Collaboration committee and the full collaboration and submitted to Physical Review Letters [2]. We successfully defended a new proposal before the JLab Program Advisory Committee (PAC) to extend our measurements of $G_M^p$ to higher $Q^2$ as part of the JLab 12-GeV Upgrade (Section 6.1.1). JLab recently received approval to begin construction on this project. The proposal E12-07-104 was approved by PAC32 in August, 2007 for running in the first five years after the 12-GeV Upgrade [3]. We have begun the analysis of the third E5 data set to

$^1$The CLAS Collaboration has a procedure where Collaboration members can analyze existing data sets with official Collaboration approval. The member writes a proposal describing an analysis project, it is reviewed by an internal committee, and then defended before the full Collaboration.

$^2$CLAS Collaboration rules require a separate technical paper to be reviewed by an internal committee before the process of publication begins.
We have copied the data to the Richmond computing cluster and completed initial calibrations, efficiency measurements, etc. (Section 6.1.1).

We have made progress in our analysis of the fifth structure function in $^2$H(e, $e_p)n$ (Section 6.1.2). This project is a CLAS Approved Analysis. The reaction was simulated with the CLAS standard Monte Carlo package GSIM and we showed that our analysis algorithms are valid. We have also extracted systematic uncertainties. A new calculation by Jeschonnek and Van Orden using a fully relativistic approach in the impulse approximation described much of our data when averaged over the CLAS acceptance [4, 5].

In other contributions, we upgraded one of the CLAS online monitoring tools (online RECSIS) to the linux operating system (Section 6.1.4). Gilfoyle continues to serve as chair of the Nuclear Physics Working Group and on the CLAS Coordinating Committee (Section 6.1.5). He also served on a review panel for the CLAS12 tracking in preparation for an external review [6] and presented an overview of the CLAS12 software and the software report at a 12-GeV Upgrade workshop [7, 8]. CLAS12 is the new detector that will replace CLAS in Hall B after the 12-GeV Upgrade at JLab. He was invited to give four talks on JLab physics [9, 10, 11, 12] and his students have made four presentations in the last two years [5, 13, 14, 15].

We now summarize our Plan of Work. We have begun the analysis of the third and remaining E5 data set to extract $G_M^n$ using the same techniques applied to other E5 data. These data could have considerable impact on the experimental situation in this $Q^2$ range where there are inconsistencies among different data sets and a recent, suggested observation of the pion cloud (Section 6.2.1). We will complete the analysis of the fifth structure function in quasielastic kinematics for the reaction $^2$H(e, $e_p)n$. We are generating Monte Carlo simulations now to test for acceptance effects in the two data sets where we see statistically significant results. We are analyzing the same data set as the $G_M^n$ experiment. Once that analysis is complete we will explore other structure functions and higher energy transfer. These measurements have the potential to establish a baseline for the hadronic model at low $Q^2$ which will enable us to more clearly see the onset of quark-gluon degrees of freedom at higher $Q^2$ (Section 6.2.2). Last, we will begin work on the simulation of neutrons for the CLAS12 detector. This project is closely connected with our future physics projects and takes advantage of our past experience (Section 6.2.4).

We propose the addition to our group of a faculty researcher in hypernuclear physics. This idea is motivated by the presence at Richmond of Dr. C. Samanta who is on a three-year teaching assignment while on leave from the Saha Institute in Kolkata, India. Her position is Visiting Instructor of Physics. Dr. Samanta is an accomplished nuclear physicist with a background that bridges both theory and experiment. She is now focused on hypernuclear physics and has joined the hypernuclear collaboration at JLab under the leadership of Dr. L. Tang and will participate in an upcoming experiment in 2009 (E05-115/E08-002) and later (depending on beam schedule) E08-012. More details are in Sections 6.2.6, 6.2.7, and 7. Dr. Samanta’s presence at Richmond is an opportunity for us to extend our physics reach, recruit and train more students, and enhance the physics program at JLab at comparatively little cost. We note here, this new program and our existing one are distinct. We will form one group of faculty and students, but there are no plans at this time for Dr. Samanta to join the CLAS Collaboration or for Gilfoyle to join the hypernuclear collaboration.
6 Project Description

6.1 Status of Current Projects

6.1.1 Magnetic Form Factor of the Neutron

The elastic electromagnetic form factors are the most basic observables that describe the internal structure of the proton and neutron. Their measurement is a goal of the current NSAC Long-Range Plan [16] and is Milestone HP4 in the DOE Performance Measures [17]. The differential cross section for elastic electron-nucleon scattering can then be calculated in the laboratory frame as [18]

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \left( G_E^2 + \frac{\tau}{\epsilon} G_M^2 \right) \left( \frac{1}{1 + \tau} \right) \tag{1}$$

where $\sigma_{Mott}$ is the cross section for scattering from a point particle, $G_E$ is the electric form factor, $G_M$ is the magnetic form factor, $\tau = Q^2/4M^2$ where $M$ is the nucleon mass, and $\epsilon = (1 + 2(1 + \tau)\tan^2(\theta/2))^{-1}$ where $\theta$ is the electron scattering angle. There are a total of four elastic form factors (electric and magnetic ones for each nucleon).

We are part of a broad assault on the four elastic nucleon form factors at Jefferson Lab [19, 20, 21]. All four elastic form factors are needed to untangle the different quark contributions and our focus is on $G_M^n$. To measure $G_M^n$ we use the ratio $R$ of quasielastic (QE) $e - n$ to $e - p$ scattering on deuterium defined as

$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(E,Q^2,\theta_{pq}^{max},W_{max}^2) \frac{G_E^{2+2+G_M^n}}{1+\tau} + 2\tau G_M^n \tan^2(\theta/2)$$

where $E$ is the beam energy, the factor $a(E,Q^2,\theta_{pq}^{max},W_{max}^2)$ corrects for nuclear effects and depends on cuts on $\theta_{pq}^{max}$, the maximum angle between the nucleon direction and the three-momentum transfer $q$, and $W_{max}^2$, the maximum value of the mass recoiling against the electron assuming the target was at rest. Deviations from the ‘free ratio’ assumption in the right-hand part of Equation 2 are parameterized by the factor $a(E,Q^2,\theta_{pq}^{max},W_{max}^2)$ which can be calculated from deuteron models and is close to unity at large $Q^2$. The ratio method is less vulnerable to systematic uncertainties than previous methods [22]. The extraction of $G_M^n$ depends on our knowledge of the other three nucleon form factors.

We have completed data collection and the analysis for a measurement of $G_M^n$ in the range $Q^2 = 1.0 - 4.8$ GeV$^2$ using two out of the three sets of running conditions from the E5 running period [1, 9, 10, 22, 23]. Our results are shown in Figure 1 for two electron beam energies (2.6 GeV and 4.2 GeV) with the CLAS toroid having standard polarity (electrons inbending) along with a selection of the world’s data. The reversed polarity (electrons outbending) data at 2.6 GeV are still being analyzed (see below and Section 6.2.1). The data are plotted as the ratio to $G_M^n/\mu_n G_D$ where $\mu_n$ is the neutron magnetic moment and $G_D$ is calculated in the dipole approximation. The data are consistent with $G_D$ for $Q^2 > 1.0$ GeV$^2$. A CLAS analysis note describing this work has been approved based on J.D.Luchetti’s thesis (a CMU graduate student) [1].

The Richmond group have taken over primary responsibility for completing the work since spring 2008 after J.D.Luchetti took a position in industry. A paper has been submitted to Physical Review Letters [2]. We have taken the lead role in writing this paper and shepherding it through the review process.

We have submitted a proposal (PR12-07-104) to measure $G_M^n$ at high $Q^2$ as part of the physics program for the JLab, 12-GeV Upgrade [3]. The proposal was approved by PAC32 in August, 2007. We had the primary responsibility for developing this proposal. The committee report [24] summarized the proposal in the following way:

Proposal PR12-07-104 is a measurement of the neutron magnetic form-factor $G_M^n$ in Hall B using a deuterium target. The method proposed is elegant and its physics essential to the program. The results of this experiment, if successful, will provide neutron data, which when combined with proton results determine the isovector form-factor, that is more readily computable on the lattice, having no disconnected quark contributions. This essential measurement will thus have the added benefit of providing a valuable test of the efficacy of lattice calculations.

\[^{2}\text{CLAS Collaboration rules require a separate technical paper to be reviewed by an internal committee before the process of publication begins.}\]
This planned measurement will significantly expand the upper limit of this measurement (from $Q^2 = 4.8$ GeV$^2$ to 13.5 GeV$^2$), provide important constraints on generalized parton distributions, and test the validity of lattice QCD calculations. We continue to study simulations of this experiment to support the design and construction of the new, CLAS12 detector in Hall B [13, 15].

The E5 run period consists of data sets with three different sets of running conditions. Two sets at 2.6 GeV and 4.2 GeV used a standard CLAS torus magnet polarity (electrons inbending) and a third set of data was collected at 2.6 GeV with the CLAS torus polarity reversed (electrons outbending) to reach lower $Q^2$. These data cover the range $Q^2 \approx 0.2 - 1.0$ GeV$^2$ and overlap with measurements from several other laboratories and other experiments at Jefferson Lab. This region has been the focus of intense interest over the last few years because of the observation of evidence for the pion cloud [36, 37]. We are now analyzing those data. We have extracted the neutron and proton detection efficiencies, calculated the Fermi correction, and carefully matched the $e^-n$ and $e^-p$ solid angles to determine $R$. A comparison with our previous results for the 2.6-GeV, normal torus polarity results show some differences that are under investigation.

In our last renewal in 2006, we planned on developing the proposal to measure $G_n^\pi M$ at 12 GeV and begin the analysis of the reversed torus polarity measurements from the E5 run period. The proposal has been approved and we have made progress on the analysis. During the same time period we have taken over and completed the CLAS analysis note and lead the effort to write the paper and submit it for publication.

### 6.1.2 Out-of-Plane Structure Functions of the Deuteron

We are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e}, e'p)n$ to establish a baseline or benchmark for the hadronic model of nuclei to meet. The data were measured with the CLAS detector in Hall B at JLab (see Section 2.2 for more details). This baseline is necessary so that we can more clearly map the transition from hadronic to quark-gluon degrees of freedom at higher $Q^2$. The cross section for the reaction with a polarized beam and unpolarized target can be written as

$$\frac{d\sigma}{d\Omega_{1e}d\Omega_{pq}} = \sigma_L + \sigma_T + \sigma_{TT} \cos \phi_{pq} + \sigma_{LT} \cos 2\phi_{pq} + h\sigma_{LT}' \sin \phi_{pq}$$

where the $\sigma_i$ are the different components of the cross section, $h = \pm 1$ is the helicity of the electron beam, and $\phi_{pq}$ is the azimuthal angle of the ejected proton relative to the 3-momentum transfer $\vec{q}$. This angle $\phi_{pq}$ is the angle between the plane defined by the incoming and outgoing electron 3-momenta and the plane defined by the ejected proton and neutron. See Figure 2. The $\phi_{pq}$-dependent parts of Eq. 3 have not been extensively investigated in the past. They represent a model-independent measurement of a little-studied part of the deuteron cross section and probe its wave function.

In this status report we focus on our progress extracting the fifth structure function $\sigma_{LT}'$ (see Eq. 3) which is the imaginary part of the $LT$ interference. The structure functions are measured by forming asymmetries. We define the asymmetry $A_{LT}$ as $A_{LT} = \sigma_{LT}' / (\sigma_L + \sigma_T)$. Note this definition is slightly different from previous ones which included an additional, small contribution from $\sigma_{TT}$ in the denominator of $A_{LT}$. For our analysis, the effect of this additional term is negligible. To take full advantage of the large acceptance of the CLAS detector we form the asymmetries from the moments of the out-of-plane production. We start...
with the $\sin \phi_{pq}$-weighted average for different beam helicities

$$\langle \sin \phi_{pq} \rangle_{\pm} = \frac{\int_{0}^{2\pi} \sigma_{\pm} \sin \phi_{pq} d\phi_{pq}}{\int_{0}^{2\pi} \sigma_{\pm} d\phi_{pq}} = \frac{1}{N_{\pm}} \sum_{i=1}^{N_{\pm}} \sin \phi_{i} = \frac{\pm A'_{LT}}{2}$$

(4)

where the pluses and minuses refer to the beam helicity, $\sigma_{\pm}$ is the cross section in Equation 3 for different beam helicities, $\phi_{i}$ is $\phi_{pq}$ for an event, and $N_{\pm}$ is summed over all events of a particular beam helicity. We then subtract the two averages to obtain the asymmetry $A'_{LT} = \langle \sin \phi_{pq} \rangle_{+} - \langle \sin \phi_{pq} \rangle_{-}$. Here we report on our results for quasi-elastic kinematics.

We are analyzing the E5 data set which is the same dataset as the $G_{M}^{n}$ measurement in Section 6.1.1. We are focused on the two, 2.6-GeV datasets with opposite torus polarities. The 4.2-GeV has inadequate statistics for our analysis. The data cover the 4-momentum transfer range $Q^{2} = 0.2 - 2.0 \,(\text{GeV/c})^{2}$. Preliminary results for $A'_{LT}$ are shown in the left-hand panel of Figure 3 as a function of the missing momentum $\vec{p}_{m} = \vec{q} - \vec{p}_{p}$ where $\vec{p}_{p}$ is the measured proton momentum. In the plane-wave impulse approximation this is the opposite of the initial momentum of the proton in the deuteron. These are the first data measured for this asymmetry in this $Q^{2}$ range. We can observe small asymmetries with good precision in quasi-elastic kinematics.
The analysis of the asymmetry $A_{LT}$ is far along. We have completed event selection, data corrections, and extracted systematic errors from the data. We are now studying acceptance effects using the CLAS standard simulation package GSIM. Some results for the 2.6-GeV, reversed torus polarity data are shown in the right-hand panel of Fig 3. Within the Monte Carlo uncertainties, the simulation agrees with the ‘true’ distribution (the red curve). We are continuing to produce these simulations to reduce the uncertainties in the calculation at high $p_m$ seen in Fig 3 and to perform the same calculations for the 2.6-GeV, normal torus polarity data set.

We have compared our results with theoretical calculations. The black curves on each plot in the left-hand panel of Fig. 3 are from Arenhövel [38] averaged over the CLAS acceptance. These calculations use the non-relativistic Schrödinger equation with relativistic corrections added along with corrections for meson exchange currents, isobar configurations, and final state interactions (FSI) [39]. Those calculations agree with the data in sign and magnitude for $p_m < 0.25 \ (GeV/c)$, but disagree at higher missing momentum. The green curves are from Jean-Marc Laget who uses a diagrammatic approach for $Q^2 = 1.1 \ \text{GeV}^2$ (lower panel) and $Q^2 = 0.7 \ \text{GeV}^2$ (upper panel) [40]. This calculation does not reproduce the shape or $Q^2$ dependence of our measurement. We have a new calculation from Jeschonnek and Van Orden (JVO) shown in the red curves which is a fully relativistic calculation in the impulse approximation using the Gross equation for the deuteron ground state and the SAID parameterization of the $N\bar{N}$ scattering amplitude for FSI. The red curves in the left-hand panel of Fig 3 are averaged over the CLAS acceptance. For the high-$Q^2$ data set, the JVO calculation reproduces our data over the full range of missing momenta. At lower $Q^2$, it does well for $p_m < 0.4 \ \text{GeV}$, but diverges at high $p_m$; a sign of the increasing importance of meson-exchange currents not included in JVO. Our recent progress on this analysis was presented at the 2008 Gordon Conference on Photonuclear Reactions.

In our last renewal in 2006, we planned on completing this analysis by 2009. We still expect to meet that schedule. This work is part of a CLAS Approved Analysis (see Table 1) and Gilfoyle is the spokesperson. Preliminary results have been presented at conferences [5] and a CLAS analysis note is in preparation.

### 6.1.3 Quark Propagation and Hadron Formation

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and the quest to understand confinement quantitatively is an essential goal of modern nuclear physics. The subject can be investigated by striking one of the quarks with a photon and stretching out the color string tying it to its neighbors. The color string stretches until $q\bar{q}$ pairs tunnel up from the vacuum, thwarting the struck quark’s attempt to escape to isolation. The real picture with full QCD is more complicated and experimental information is necessary to guide models of hadronization. Gilfoyle is a co-spokesperson on a 12-GeV experiment E12-06-117 Quark Propagation and Hadron Formation that lays out a program to determine the mechanisms of confinement in forming systems. We are responsible for the analysis of the $\pi^0$, $\eta$, and $\eta'$ exit channels. This future experiment and E12-07-104 (the 12-GeV $G_M$ measurement) have motivated our interest in the detection of neutral particles as part of the CLAS12 software development and the 12-GeV Upgrade.

### 6.1.4 Technical Projects

We are committed to development projects for the JLab 12-GeV Upgrade and will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction in CLAS12, the new detector in Hall B [41]. We have begun work using an early version of the CLAS12 simulation package called Sim12. We optimized and documented the procedures needed to download, install, compile, and build Sim12 [42] and optimized the configuration for faster response during run-time. We wrote plugins for different event generator output formats. After a core software program is written and distributed, any updates, critical or not, are difficult to distribute if the program is large and requires long recompilation times like Sim12. Plugins, on the other hand, can be extremely easy to implement by a user, often involving a single download into a specific directory as the only necessary step to gain or improve functionality. We developed two plugins to read in event generator results and pass them to Sim12; one using a text-based event format and the other using the LUND format [43]. The code was tested with three different Linux distributions along with initial physics testing [14]. Since then, the CLAS12 software group has developed a
new program called gemc to replace Sim12. We are now getting this new package operational at Richmond [15].

We are also responsible for maintaining one of the current CLAS online monitoring tools called online RECSIS [44, 45]. The CLAS collects data at a prodigious rate so it is essential that the incoming data be carefully monitored to enable early detection of any problems. We modified the CLAS standard analysis package to read the incoming datastream during an experiment and perform a full, event reconstruction on a subset of the incoming data. Histograms have been developed for monitoring purposes and these are used to generate timelines of various quantities that be observed using a web-based interface. The code has been operating reliably for years now and we modified it in fall, 2007 to use the Linux operating system when the Hall B DAQ group switched to that operating system.

6.1.5 CLAS Collaboration Service

Gilfoyle was part of the team that assessed the design of the CLAS12 drift chambers during a workshop on this topic at JLab in February, 2007 [6] in preparation for an external review of the systems. At the Hall B, 12 GeV Workshop in May, 2007 he presented the progress on the CLAS12 reconstruction and gave the report on the software portion of the workshop. He serves as chair of the Nuclear Physics Working Group and is a member of the CLAS Coordinating Committee; the primary governance committee of the CLAS Collaboration. Each physics working group in the Collaboration (there are four) is responsible for discussing, planning, and reviewing physics issues and their consequences for the CLAS instrumentation in their designated subfield [46].
6.2 Plan of Work

The research effort in nuclear physics is part of the program at the Thomas Jefferson National Accelerator Facility (JLab) in Newport News, VA. The primary goal of JLab is to unravel the quark and gluon structure of protons, neutrons, and atomic nuclei and to deepen our understanding of matter and, in particular, the confinement of quarks. In this section we describe the experimental environment and the proposed physics programs.

JLab is a unique tool for basic research in nuclear physics. The central instrument is a superconducting electron accelerator with a maximum energy of 4-6 GeV, a 100% duty cycle, and a maximum current of 200 µA. Our research is done in Hall B with the CEBAF Large Acceptance Spectrometer (CLAS) and here we propose a new program in Hall C in hypernuclear physics. CLAS is a large (45-ton), toroidal, multi-gap magnetic spectrometer with nearly full solid angle coverage (see Figure 4). A toroidal magnetic field is generated by six iron-free superconducting coils. The particle detection system consists of drift chambers [47] to measure charged particle trajectories, Cerenkov detectors [48] to identify electrons, scintillators [49] for time-of-flight measurements, and electromagnetic calorimeters [50]. The six segments are instrumented individually to form six independent spectrometers. The Richmond group has been part of the CLAS Collaboration that built and now operates the detector since its inception.

The base equipment in Hall C consists of the moderate-resolution, 7-GeV/c High-Momentum Spectrometer and the large-acceptance Short-Orbit Spectrometer. For the hypernuclear experiments described below these detectors will be moved to make space for the High-Resolution Kaon Spectrometer (HKS) and High-Resolution Electron Spectrometer (HES) (see Figure 5). To reach very forward angles, a splitter magnet separates positive kaons, scattered electrons, and zero-degree electrons. The chicane in the figure is required so the zero-degree electrons reach the Hall C beam dump.

JLab recently received approval from DOE to begin a project to double the CEBAF energy and expand the physics reach of the laboratory. The completion of the 12-GeV CEBAF Upgrade at JLab is Recommendation 1 of the most recent Long-Range Plan of the Nuclear Science Advisory Committee [16]. To take advantage of the new physics opportunities a new detector called CLAS12 will be built in Hall B to replace the existing CLAS. We are committed to development projects for the JLab 12-GeV Upgrade and will be responsible for design, prototyping, development, and testing of software for event simulation and reconstruction.

Figure 4: The CLAS detector.
6.2.1 Magnetic Form Factor of the Neutron (Gilfoyle)

One of the central goals of nuclear physics now is to push our understanding of the theory of the strong interaction, Quantum Chromodynamics or QCD, into the unconquered territory of the nonperturbative region [16]. Here, the nonlinear nature of QCD dominates and defies traditional mathematical solutions; forcing us to resort to phenomenological models, effective field theories, and the daunting numerical calculations of lattice QCD. Our understanding of the structure of the proton and neutron is still clouded. One of the central questions raised in The Frontiers of Nuclear Science is ‘What is the internal landscape of the nucleons?’ [16].

The neutron magnetic form factor $G_n^M$ is one of the fundamental quantities of nuclear physics and its evolution with $Q^2$ characterizes the distributions of charge and magnetization within the neutron. It is central to our understanding of nucleon structure. We are now opening a new, unprecedented tomographic view of the interior of the nucleons through the measurement of generalized parton distributions (GPDs). The elastic form factors are a limiting case related to the zeroth moment of the GPDs and provide a vital constraint to GPD models [51]. Lattice QCD calculations are now becoming feasible in the few-GeV $^2$ range, and over the next decade these calculations will become increasingly precise [52]. The elastic form factors here for both the proton and neutron are an important test case of the accuracy of the lattice calculations. With them, one can determine the isovector combinations of the form factors [53] which are easier to calculate on the lattice because of the lack of disconnected contributions [24]. We are part of a wide effort to measure the four elastic nucleon form factors at Jefferson Lab [19, 20, 21]. All four elastic form factors are needed to untangle the different quark contributions and our focus is on the magnetic form factor of the neutron. Our role in the $G_n^M$ project is twofold. First, we have taken on the task of analyzing the 2.6-GeV, reversed torus polarity (electrons outbending) data from the E5 running period. The goal is to extract $G_n^M$ using the same methods developed for the other sets of running conditions at 2.6 GeV and 4.2 GeV (both have normal torus polarity with electrons inbending). Second, we propose developing software for simulating the performance of the CLAS12 detector which will occupy Hall B after the 12-GeV Upgrade.

The current status of our understanding of $G_n^M$ at lower $Q^2$ is shown in Figure 1 in Section 6.1.1 where $G_n^M$ is scaled by the dipole form factor $G_D(Q^2) = 1/(1 + Q^2/\Delta)^2$ and $\Delta = 0.71$ GeV$^2$. The parameter $\Delta$ is interpreted as the square of the effective meson mass. The red points represent the recent work by Lachniet, et al. and our E5 group [2, 22, 23]. The blue triangles are a recent Hall A measurement at JLab by Anderson, et al. using the $^3$He($e^-,e'p$) reaction in concert with theoretical calculations to extract $G_n^M$ [26]. The remaining points are from several experiments including precise measurements of the reduced form factor by Anklin, et al [29] and Kubon, et al. [54] that use the ratio method similar in many respects (but not all) to the method we use and which is described below. We focus here on $Q^2 < 1.0$ GeV$^2$. Our measurement in Fig. 6.1.1 at $Q^2 = 1.0$ GeV$^2$ is about 6-7% below the one by Kubon et al. (open circle) at nearly the same $Q^2$. The data from Anklin et al. (open triangles in Fig. 6.1.1) range from 2-5% above the dipole and are a few percent
above the Anderson et al. results where they overlap. We have preliminary results in this $Q^2$ range that agree with Anderson et al. and are about 6-7% below the results of Anklin et al. and Kubon et al.. We have data from the E5 running period that is still being analyzed that overlaps with the other measurements in this $Q^2$ region. In particular, for the 2.6 GeV, normal torus polarity data set discussed in Section 6.1.1 we have some data that extends down to $Q^2 \approx 0.5$ GeV$^2$. We also have data from the 2.6 GeV reversed torus polarity data set that goes even lower; down to $Q^2 \approx 0.2 - 0.3$ GeV$^2$ that is still being analyzed.

We have taken on the analysis of the existing, 2.6-GeV, reversed-torus-polarity data set from the E5 running period. These data cover the range $Q^2 = 0.2 - 2.0$ GeV$^2$ and overlap with our 2.6-GeV, normal-torus-polarity data set and with the results from several other groups. See Figure 1. There are disagreements between our data and some of the previous measurements and our low-$Q^2$ data could help sort out the experimental situation. At the same time, efforts by Friedrich and Walcher [36] to re-analyze the low-$Q^2$ data for all four quasielastic, nucleon form factors suggest that a structure they observe at $Q^2 \approx 0.2$ GeV$^2$ in all the elastic form factors is due to the presence of the pion cloud. Measurements of $G_E^n$ and $G_M^n$ from Bates [37], of $G_E^p$ from Mainz [55], and of $G_M^p$ from JLab [56], have shown structure in this $Q^2$ region ($\approx 0.1 - 1.0$ GeV$^2$). Additional theoretical work supports the observation of the pion cloud [57, 58]. There are hints of structure around $Q^2 \approx 0.38$ GeV$^2$ in the ratio $G_E^p/G_M^p$ from polarization measurements in a recent Hall A experiment [59]. However, others disagree. The observation of a structure near $Q^2 \approx 0.2$ GeV$^2$ contradicts what is known from chiral perturbation theory and dispersion relations [60]. A recent measurement of $G_E^n$ from Bates [61] found no evidence of a bump due to the pion cloud. Our low-$Q^2$ CLAS data reach down into this $Q^2$ range and could overlap with the bump observed in Ref [36]. We expect statistical and systematic uncertainties of about 3% each and the E5 data set has abundant overlaps and consistency checks to ensure the quality of the results. This is an excellent opportunity to improve our understanding of nucleon structure with data we already have in hand.

To this end we will use the ratio $R$ of $e - n$ to $e - p$ scattering from a deuterium target to measure $G_M^n$. The technique is based on Equation 2 in Section 6.1.1 which shows that knowledge of $R$, nuclear correction factors $a(E, Q^2, \theta_{pq}, W_{max}^2)$, and the other elastic, nucleon form factors will enable us to extract $G_M^n$. To determine $G_M^n$ we calculate the corrections $a(E, Q^2, \theta_{pq}, W_{max}^2)$ in Equation 2 with existing models [22]. The proton form factors are precisely known and the neutron’s electric form factor is typically small. By taking ratios in Equation 2 we are less sensitive to uncertainties in the luminosity, electron acceptance, electron reconstruction efficiency, trigger efficiency, the deuteron wave function, and radiative corrections. This technique does require precise knowledge of the neutron detection efficiency and careful matching of the neutron and proton acceptances. To measure the neutron detection efficiency a unique dual, hydrogen-deuterium, target cell was used in the E5 running period. We use the $e p \rightarrow e' \pi^+ n$ reaction as a source of tagged neutrons to measure the neutron efficiency simultaneously with data collection on deuterium. The neutrons are detected in two, overlapping measurements with both the electromagnetic calorimeter (EC) and the time-of-flight (TOF) system in CLAS. The TOF measurement provides a useful cross check on the EC measurement. To measure the proton detection efficiency we use elastic $e p$ scattering on the hydrogen target to make tagged protons. Acceptance matching is done event-by-event by detecting the electron and assuming quasielastic scattering from one of the nucleons in deuterium. We then use the electron kinematics to determine if a quasielastic proton or neutron would fall in the CLAS acceptance. If so, then we search for a proton or neutron in the predicted locations. Corrections for Fermi motion of the nucleons bounds in the deuteron are calculated in simulation. To select quasielastic events we make a cut on $\theta_{pq}$ the angle between the detected nucleon and 3-momentum transfer $q$ which effectively eliminates inelastic events for $W^2 < 1.2$ GeV$^2$ [2]. This method has proved successful in our previous analysis of the E5 data [2].

During the period of this proposal we will perform the analysis of the 2.6-GeV, reversed field data described above. We will be working with W.K. Brooks (JLab) the spokesperson on the original $G_M^n$ proposal (E94-017). Dr. Brooks is now at the Universidad Técnica Federico Santa María in Chile, but spends considerable time at JLab each year. The analysis of these data and fifth-structure function data (see Section 6.1.2 and below) are from the same dataset so we can make efficient use of our time and resources.

### 6.2.2 Out-of-Plane Structure Functions of the Deuteron (Gilfoyle)

We propose to measure the out-of-plane structure functions of the deuteron in the GeV region to test the hadronic model of nuclear physics. The hadronic model of nuclear physics has been successful at low $Q^2$, but it
is not well-developed in the GeV region even though we expect it to be valid there. There are few data to challenge theory. The importance of relativistic corrections (RC), final-state interactions (FSI), meson-exchange currents (MEC), and isobar configurations (IC) is our focus here. These measurements complement an effort on the theory side to clarify our understanding of the hadronic picture of the deuteron [62]. Our project is part of a larger effort to establish a baseline for the hadronic model to meet so deviations at higher $Q^2$ can be attributed to quark-gluon effects with greater confidence. This is an important step in answering the question posed in the most recent NSAC Long-Range Plan: ‘What governs the transition from quarks and gluons to pions and nucleons?’ [16]. The importance of this issue was stressed in previous JLAB PAC studies [63].

As mentioned in Section 6.1.2 we are investigating the out-of-plane structure functions of the deuteron using the reaction $D(\vec{e},e'p)n$ with CLAS. See Eq. 3 and Fig. 2 in Section 6.1.2 for the expression for the cross section and the kinematic observables. The structure functions are an essential meeting ground between theory and experiment and the unique, nearly-$4\pi$ solid angle of CLAS coupled with the high-quality, polarized beams at JLab create an inviting opportunity to study $\sigma'_{LT}$, $\sigma_{LT}$, and $\sigma_{TT}$ (see Eq. 3). These structure functions depend on $\phi_{pq}$ and have not been extensively investigated in the past. We are making a model-independent measurement of a little-studied part of the deuteron cross section that probes its wave function. The large acceptance of CLAS gives us the capability of accessing a wide range of $Q^2$ and energy transfer $\nu$.

We now discuss the present state of knowledge of these out-of-plane structure functions of the deuteron. Existing measurements of $A'_{LT}$ are sparse. There are two measurements of $A_{LT}$ in quasielastic kinematics at $Q^2 = 0.13$ GeV$^2$ [64] and 0.22 GeV$^2$ [65] and a single measurement at higher energy transfer $\nu$ at $Q^2 = 0.15$ GeV$^2$ [66]. The effect of FSI is shown in Fig. 6 from Ref. [65] where the solid curve is a calculation with FSI turned on and the dashed-dotted line shows the same calculation with FSI turned off. The same figure also shows the challenges of making these measurement with adequate statistics. Compare Fig. 6 with our preliminary measurements in Fig. 3. Measurements of $A_{TT}$ are equally sparse. There are three quasielastic measurements [65, 67, 68] and a single one at higher $\nu$ [66]; all are for $Q^2 < 0.22$ GeV$^2$. Again, these measurements suffer from large uncertainties and limited coverage at large $p_m$ which is the best region for distinguishing between competing theories. For the asymmetry $A_{LT}$, the situation is better. There are several measurements in quasielastic kinematics that cover the range $Q^2 = 0.013$ GeV$^2$ to 1.2 GeV$^2$. At low $Q^2$ nonrelativistic calculations reproduce the data [67] while at $Q^2 = 1.2$ GeV$^2$ relativistic calculations are preferred [69]. Between these extremes the situation is less clear; there is a significant spread in the calculations [70]. There is a single measurement at higher $\nu$ [66].

We have been working with several theory groups which we discussed in Section 6.1.2. The fifth structure function is a sensitive probe of the spin-orbit part of the $NN$ interaction. The plot in Fig 7 shows the calculated $A'_{LT}$ from Jeschonnek and Van Orden (JVO) [71]. With the spin-flip scattering amplitude turned off (green, dotted curve), $A'_{LT}$ goes nearly to zero. The red, dashed curve shows a dramatic effect when the spin-orbit part is turned on in the calculation. The double-spin components (solid curve) have little effect implying the spin-orbit part of the interaction is the primary contributor.
In the period for this proposal, we will complete the analysis of the $\sigma'_{LT}$ results and move on to the other two structure functions $\sigma_{LT}$ and $\sigma_{TT}$ in quasielastic kinematics using similar analysis methods. These other structure functions may present a greater challenge because of their sensitivity to background asymmetries created by misalignments in CLAS [72]. This project is a unique opportunity to measure the three, out-of-plane, $\phi_{pT}$-dependent, structure functions in a model-independent way from a single experiment that covers a large $Q^2$ range under a common set of experimental conditions. Once that analysis is complete, we will investigate higher energy transfer (i.e., the ‘dip’ region). The JVO calculations described above can also be done for higher energy transfers so there is an excellent opportunity here to cover a wide range of kinematics with a single experiment and compare it with the most modern theory. We have a chance here to untangle these different effects and establish a hadronic model baseline.

6.2.3 Quark Propagation and Hadron Formation (Gilfoyle)

The confinement of quarks inside hadrons is perhaps the most remarkable features of QCD and its understanding is a central challenge in nuclear physics. We will investigate the nature of confinement by studying the hadronization process across a wide range of nuclei. This will enable us 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). These physics goals are focused on one of the central questions raised by the NSAC Long-Range Plan [16] ‘What governs the transition of quarks and gluons into pions and nuclei?’ A proposal (E12-06-117) for this experiment as part of the physics program for the JLab 12-GeV Upgrade was submitted and approved by the JLab PAC in the summer of 2006 [73]. Gilfoyle is a co-spokesperson on the proposal and is responsible for analysis of the $\pi^0$, $\eta$, and $\eta'$ channels along with K. Joo from the University of Connecticut. During the period of this grant we will begin work on the simulation of events in the upgraded CLAS detector (CLAS12). More details can be found in Section 6.2.4.

6.2.4 CLAS12 Simulation (Gilfoyle)

We now discuss our plans to support the completion of the 12-GeV CEBAF Upgrade at JLab [16] mentioned in Section 6.2. Event simulation is an essential aspect of the design of CLAS12 and eventual precision of the detector. For many experiments, the quality of the results will be limited by systematic uncertainties instead of statistical ones so accurate, precise calculations of the CLAS12 acceptance and response are essential. We anticipate needing about four times as much Monte Carlo data as CLAS12 collects. The CLAS12 simulation will produce data more slowly than the detector itself by about a factor of $10^3$ (a $\approx 10$ Hz for the simulation versus $\approx 10$ kHz in CLAS12).

The motivation for our group is to support our experiments that are part of the 12-GeV Upgrade in Hall B (see Table 1). Experiment E12-07-104 will measure the neutron magnetic form factor $G_M^n$ out to $Q^2 =$
The neutron measurement will be done with both the electromagnetic calorimeters and the TOF system providing an important consistency check as in our previous measurement [1]. Fig. 8 shows a drawing of the CLAS12 detector including the electromagnetic calorimeter (EC) that will be reused from CLAS. Over most of the $Q^2$ range we will have excellent statistical precision so that understanding the CLAS12 response to neutrons is important for extracting $G_M^n$ with the anticipated systematic uncertainty. Experiment E12-06-117 will focus on the physics of quarks moving through nuclear matter and how they evolve to fully-formed hadrons (see Sections 6.1.3 and 6.2.3). Our responsibilities are to study the electroproduction of $\pi^0$, $\eta$, and $\eta'$ from nuclear targets. The detection of each particle relies on resolving photons from their decay: $\pi^0 \rightarrow 2\gamma$, $\eta \rightarrow 2\gamma$, and $\eta' \rightarrow \pi^+\pi^-\eta$ where the $\eta$ in the $\eta'$ decay will also be detected via its $2\gamma$ decay. Detection will be done in the existing EC (reused in CLAS12) augmented by a pre-shower calorimeter (PCAL) located in front (see Fig. 8). The PCAL will have higher segmentation than the EC to insure adequate spatial resolution to separate the two photons from the $\pi^0$ and $\eta$ decays up to maximum momenta of 9 GeV. The Forward Detector (see Fig. 8) of CLAS12 will be able to detect all charged and neutral particles emitted in the polar angular range of 5 to 40 degrees.

We now describe the current status of the neutron simulation in CLAS12. The CLAS12 simulation package called gemc (for Geant4 Monte Carlo) is a Geant4-based simulation package with the following features: C++ language, object-oriented architecture, GUI interface, mysql database used for geometry, hits, magnetic field, materials, and physics output [74, 75, 76]. The TOF system has been implemented in the code, but only limited studies of its performance have been done. The EC and PCAL code has not been written. For neutron simulation one can choose a variety of physics algorithms to describe the process, but none have been tested with the CLAS12 geometry. From our experience in CLAS we know there are differences between the neutron detection efficiency measured in CLAS [2] and the same quantity derived from the current Geant3-based CLAS simulation called GSIM [77]. We are now investigating those differences in our analysis of the low $Q^2int{G_M^n}$ data (see Section 6.2.1).

In order to have an adequate CLAS12 neutron simulation a number of tasks must be completed. (1) The EC and PCAL geometries have to be implemented in gemc. (2) A materials database is needed to provide the information on the composition of each component of the EC and PCAL. (3) The Geant4 algorithms for ‘swimming’ tracks through CLAS12 need to be tested in gemc. (4) We then construct the detector information produced by the track (digitization) and (5) test the results. To test the neutron simulation in CLAS12 we will use our experience from CLAS on the neutron detection efficiency on the
EC. If the simulation and the measured, CLAS neutron detection efficiency are consistent, then we have
greater confidence in our results when we add in the PCAL. The simulation will likely be a part of the
CLAS Reconstruction and Analysis Framework (Clara). Clara is an implementation of a service-oriented
architecture (SOA) which grew out the older concepts of distributed computing and modular programming
[78, 79]. It’s goal is to provide a single framework which can be applied to the full range of physics data
processing applications for the CLAS12 experiments. CLARA is currently a JLab research project under
the direction of Vardan Gyurjyan and with his help we have begun using the Richmond computing cluster
as a test bench for Clara.

For the period of this proposal we intend to begin work on the CLAS12 neutron simulation in gemc. This
will involve testing the neutron simulation with the existing CLAS12 TOF system that has been implemented
in gemc and installing the EC and PCAL geometry. We can then begin testing the simulation using our
results from CLAS as a benchmark. We will be working with M. Ungaro at JLab who is now the lead
developer for gemc. As the software matures we will make it a service in Clara with help from the lead
developer V. Gyurjyan. We note here that Gilfoyle has long experience with CLAS software. He was one of
the early developers of the primary CLAS reconstruction software (RECSIS) and developed and maintains
one of the CLAS online monitoring tools (online RECSIS [44, 45]).

6.2.5 CLAS Collaboration Service (Gilfoyle)

During the period of this proposal we will continue to maintain the code for calculating radiative corrections
for exclusive reactions on the deuteron [44, 45] and to maintain online RECSIS, one of the CLAS data-
acquisition monitoring tools. This will be in addition to normal Collaboration duties. Finally, Gilfoyle is
now chair of the Nuclear Physics Working Group and member of the CLAS Coordinating Committee, the
main governing body of the Collaboration.

6.2.6 Hypernuclear Program (Samanta)

We propose here a new program to study hypernuclear at the University of Richmond. This project is
motivated by the presence at Richmond of Dr. C. Samanta for the next three years on a teaching assignment
from the Saha Institute in India (see Section 6.2.7). The focus of the project is to understand the little-known
hyperon-nucleon (YN) interaction which could provide additional insight important for our understanding of
neutron stars and the time-evolution of supernova. These topics are discussed in the NSAC Long-Range Plan
[16] and DOE Milestones HP10 and NA8 [17]. To this end Dr. Samanta has joined the E05-115/E08-002
collaboration to measure the spectra and binding energies of Λ hypernuclei across a wide mass range using
the (e, e′K+) reaction (see Table 1). This experiment has been rated Λ− by the PAC and is scheduled to run
in 2009 in Hall C. It builds on a previous experiment E01-011 in 2005 by many of the same collaborators.
Dr. Samanta has also joined the collaboration for a related experiment E08-012 to study hypernuclei via
their pionic decay. This experiment has been rated Λ− by the PAC and is not yet scheduled (see Table 1).

Dr. Samanta’s relevant expertise is her theoretical work on the masses and binding energies of hypernuclei.
The variation of the binding energy of hypernuclei with mass number A is expected to be exotic. Earlier,
Dover and Gal [80] prescribed two separate mass formulae for Λ and Ξ hypernuclei by introducing several
volume and symmetry terms in Bethe-Weizsäcker mass formula (BW). There after Levai et al., [81] proposed
a BW equation inspired by the spin-flavour SU(6) symmetry in which the pairing term of BW was replaced by
the expectation value of the space-exchange or, Majorana operator and a strangeness dependent symmetry
breaking term was also added. Both formulae have severe limitations described in Refs [82, 83]. None of these
formulations had explicit hyperon mass consideration, they can not be used for binding energy calculation
of other kind of hypernuclei.

Wigner’s SU(4) symmetry arises as a result of the combined invariance in spin (I) and isospin (T). In
order to incorporate the strangeness degree of isospin, SU_T (2) is replaced by SU_F (3) and the combined
spin(I)-flavour(F) invariance gives rise to the SU(6) classification of Gursey and Radicati [84]. The SU_F (3)
symmetry breaks by explicit consideration of a mass dependent term in a mass formula. The SU(6) symmetry
breaking is related to different strengths of the nucleon-nucleus and hyperon-nuclear interactions and has
important consequences. For example, although small, the Σ−Λ mass difference figures prominently in the
smallness of the Λ-nuclear spin-orbit interaction [85] which is a topic of interest in the current experimental
studies.
A generalized mass formula for normal nuclei and strange hypernuclei was developed by us [82, 83] in which the non-strange normal nuclei and strange hypernuclei are treated on the same footing with due consideration to SU(6) symmetry breaking. The generalization of the mass formula is pursued starting from the modified-Bethe-Weizsacker mass formula (BWM) preserving the normal nuclear matter properties. The BWM is basically the Bethe-Weizsacker mass formula extended for light nuclei [86, 87, 88, 89] which delineated several zones in nuclear chart where some new magic number appear and some known magic numbers disappear. This mass formula can explain the gross properties of binding energy versus nucleon number curves of all non-strange normal nuclei up to Z=83. This generalized mass formula will be employed to deduce the binding energies of all Λ hypernuclei in the entire nuclear chart up to Z = 83. The limits of stability of Λ hypernuclei [90, 91] as well as other hypernuclei will be explored in detail.

The total binding energy of a hypernucleus of total mass number A and net charge Z containing charged or neutral hyperon(s) is given by [82, 83]:

\[
B(A, Z) = 15.777A - 18.34A^{2/3} - 0.71 \frac{Z(Z - 1)}{A^{1/3}} - 23.21(N - Zc)^2 \frac{1}{(1 + e^{-A/17})A} + (1 - e^{-A/30})\delta + n_Y[0.0335(m_Y) - 26.7 - 48.7|S|A^{-2/3}]
\]

(5)

where \(\delta = 12A^{-1/2}\) for \(N, Zc\) even, \(\delta = -12A^{-1/2}\) for \(N, Zc\) odd, and \(\delta = 0\) otherwise, \(n_Y\) = number of hyperons in a nucleus, \(m_Y\) = mass of the hyperon in MeV, \(S\) = strangeness of the hyperon and mass number \(A = N + Zc + n_Y\) is equal to the total number of baryons. \(N\) and \(Zc\) are the number of neutrons and protons respectively while the \(Z\) in Eq. 5 is given by \(Z = Z_c + n_Yq\) where \(q\) is the charge number (with proper sign) of hyperon(s) constituting the hypernucleus. For non-strange (\(S=0\)) normal nuclei, \(Z_c = Z\) as \(n_Y = 0\). The choice of \(\delta\) value depends on the number of neutrons and protons being odd or even in both the cases of normal and hypernuclei. For example, in case of \(^{13}\text{C}\), \(\delta = +12A^{-1/2}\) as the \((N, Z_c)\) combination is even-even, whereas, for non-strange normal \(^{13}\text{C}\) nucleus \(\delta = 0\) as \(A=13\) (odd). The hyperon term (last term in equation 5) reflects SU(6) symmetry breaking through explicit consideration of the different masses of different hyperons. The three coefficients of the hyperon term were obtained by minimizing root mean square deviation of the theoretical hyperon separation energies from the experimental ones. The hyperon separation energy \((S_Y)\) is defined as \(S_Y = B(A, Z)_{\text{hyper}} - B(A - n_Y, Zc)_{\text{core}}\) which is the difference between the binding energy of a hypernucleus and the binding energy of its non-strange core nucleus.

In hypernuclear production, most of the states are excited as nucleon-hole-particle states, \((N^{-1}, A)\). The spreading widths of these states were calculated to be less than a few 100 keV [92, 93]. This occurs because: 1) The isospin is 0 and only isoscaler particle-hole modes of the core nucleus are excited; 2) the \(\Lambda N\) interaction is much weaker than the nucleon-nucleon interaction; 3) the \(\Lambda N\) spin-spin interaction is weak and therefore the spin vector p-h excitation is suppressed; and 4) There is no exchange term. An accurate knowledge of the excited states of the \(\Lambda\) hypernuclei is essential for the experimental projects undertaken at JLab.

A central \(\Lambda N\) potential has been found on the basis of an analysis of the binding energies of 1s shell hypernuclei and \(\Lambda p\) scattering [94]. Within the experimental errors, this potential makes it possible to reproduce the binding energies of three-, four-, and five-particle ground and excited states of hypernuclei and the angular and energy dependences of the cross sections for \(\Lambda p\) scattering. Within the \(\Lambda\) plus core model, the potential VAN will be matched with binding energies of heavy hypernuclei deduced by our mass formula. The excited states of the hypernuclei relevant to this experiment and other nuclei will be calculated.

During the period of this proposal Dr. Samanta will perform the following.

1. Take part in the installation, commissioning, and running of the HES and HKS (see Fig. 5) for the E05-115/E08-002 experiment. Dr. L. Tang, the collaboration leader notes that the E05-115/E08-002 collaboration has only about half the number of postdocs and graduate students as the previous, similar hypernuclear experiment E01-001 performed in 2005. Dr. Samanta’s contribution will be an important addition. It is also an excellent opportunity for undergraduate involvement since much of this activity will take place in summer 2009.

2. The knock out reaction data can in principle provide valuable information on the spin-parity of the state involved if the energy sharing spectra is plotted. To achieve this goal she will start by analyzing the existing data from a previous experiment E01-011 which was performed in 2005.

3. Dr. Samanta will then carry out the same analysis for E05-115/E08-002 and later on for E08-012.
4. With existing codes Dr. Samanta will calculate the hyperon binding energy of all the possible products in the proposed reactions as well as other hypernuclei up to $Z = 83$ and study the limits of stability of charged and neutral hypernuclei in search of exotic nuclei beyond the normal drip lines. This will be important in the planning for E08-112.

5. Dr. Samanta will begin development of her calculations to include the excited states of the hypernuclei relevant to these experiments.

The leader of the hypernuclear collaboration for these experiments, Dr. L. Tang expresses his support for Dr. Samanta in a letter in Figure 9. We note here, this new program and our existing one are distinct. We will form one group of faculty and students, but there are no plans at this time for Dr. Samanta to join the CLAS Collaboration or for Gilfoyle to join the hypernuclear collaboration.

6.2.7 Faculty Researcher (Samanta)

As discussed in Section 6.2.6 we propose the addition of a faculty researcher to the research program in medium energy nuclear physics at the University of Richmond. The addition would provide funding for summer salary and student stipends for Dr. Chhanda Samanta. Dr. Samanta is a distinguished researcher from the Saha Institute Of Nuclear Physics in Kolkata, India who now holds a three-year teaching position as a Visiting Instructor of Physics at the University of Richmond. Her duties are to teach full-time during the academic year, but she has no teaching duties during the summer. Dr. Samanta’s research career started by investigating nuclear structure using hadronic probes, but over the last three years she has focused on the effect of hyperons on the masses of nuclei. Since arriving in the US she has joined the hypernuclear collaboration at JLab led by L. Tang. The work she has done for the hypernuclear collaboration and her plan of work are described in Section 6.2.6. At Richmond, she has already started to build a group of undergraduates who would work in our research group during the summer.

The benefits of adding Dr. Samanta to our program at Richmond are twofold. (1) She will raise the physics productivity at Richmond and in the hypernuclear program at JLab. She is experienced in both experiment and theory and has a clearly defined role in the upcoming Hall C experiments described in Section 6.2.6. The group leader for the hypernuclear collaboration, Dr. L. Tang, has said she can become a ‘major player’ in the hypernuclear program (see letter in Fig. 9). (2) She will mentor undergraduates at Richmond so we can maintain a larger, more diverse, more robust research group. We typically support 2-4 students in the summer in our research group and that number will grow. Adding Dr. Chhanda will enable to expand the size of that group and create a more supportive and lively environment for our students to learn nuclear physics.

6.3 Education of Students: Undergraduate Research at the University of Richmond

Undergraduates are part of all stages of this physics program and the funds requested will enable us to provide an intense summer research experience for these young people. Since 1987 Gilfoyle has mentored 2-3 undergraduates doing research almost every summer with about two-thirds going on to graduate school in science and engineering at places like UC Santa Barbara, Virginia, Princeton, and Stanford. Five have received doctorates. Three from our lab are currently staff scientists at NASA-Goddard, NASA-Huntsville, and the Jet Propulsion Laboratory, one is a faculty member at Stanford, and one is a researcher at Cornell in biological physics. Among students who recently worked in our laboratory one (Burrell) is in graduate school in applied mathematics and physics at Christopher Newport University and another (Gill) is in graduate school in computer science at Columbia. Our students use modern computational techniques for simulation and to ‘mine’ large data sets for information using our supercomputing cluster. They take shifts at JLab, attend collaboration meetings, and present their work at local, national, and international conferences [5, 13, 14, 15]. In the last two summers four students worked in my laboratory each summer including a high school student who produced Fig. 2. They were funded by a mixture of DOE grant and University funds.
6.4 Institutional Support and Resources

6.4.1 Facilities and Support for Nuclear Physics

The nuclear physics group at the University of Richmond is supported by a computing cluster for our exclusive use. An array of student workstations is used for software development and non-CPU-intensive tasks. The system consists of 30, dual-processor machines running the Linux operating system and 3 TByte of RAID storage. Each machine has 18 GByte of disk space and 256 MByte of memory. The entire system resides on its own subnet and another machine acts as a firewall. It is in a laboratory equipped with a 5-ton, 60,000-BTU air conditioner, an upgraded electrical panel, and backup power. The support computers are located in an adjacent room; all in the Physics Department research area. It is worth noting this cluster plays two important roles. (1) It relieves pressure on the JLab computing farm. Batch jobs there can sometimes take more than a day before they are submitted. (2) The rapid turnaround on our cluster creates a compelling learning experience for our students. They get rapid feedback on their work instead of waiting for their batch jobs to be submitted on the JLab farm.

The University provides has a Linux expert on its information services staff who is responsible for keeping the CLAS software up-to-date, updating the Linux software on the cluster and in our laboratory, and general troubleshooting. The University also supports undergraduate summer stipends and student travel. We had one University-supported student in summer 2007 which allowed us to support more students in 2008. The student posters cited in Section 6.3 had travel support from the University and the American Physical Society in some cases. The University will support routine faculty travel to JLab at the level of $\approx$2,500 per year per for each senior person on the grant.

6.4.2 Proximity to Jefferson Lab

Jefferson Lab is 75 miles from the University of Richmond enabling us to maintain frequent contacts with the scientific staff and users at JLab. Gilfoyle spends about 1 day each week at JLab in addition to time spent on shift, at Collaboration meetings, etc. The work on $G_M^a$ was done in collaboration with W.K. Brooks, a former JLab staff scientist who is now at Universidad Técnica Federico Santa María in Chile, but spends considerable time at JLab each year. We will continue to collaborate on the work described here. The CLAS12 software is now done primarily by the CLAS12 software at JLab (M. Ungaro, D. Weygand, and V. Gyurjyan) and Gilfoyle will be collaborating with them. We also take students on shift with us and attend Collaboration meetings at little cost. The University supports routine faculty travel to JLab.

6.4.3 Sabbatical Leave

The PI (Gilfoyle) will be on sabbatical leave during the first year of this proposal (2009-2010) and will use that time to work on the project described here. He is currently pursuing funding in order to spend the full year on sabbatical.
October 31, 2008

To Whom It May Concern,

I am strongly endorsing Professor Chhanda Samanta’s application for fund support on her research at JLAB. As I understood, the application is to request addition of her into Prof. J. Gilfoyle’s existing DOE grant.

Prof. Chhanda Samanta is a new full time faculty at Physics Department, Gottwald Science Center, University of Richmond. She has both experimental and theory background and has strong interest in the highly exotic Lambda-hypernuclei. She had some recent publications on the predictions of the maximum neutron number that Lambda-hypernuclei can have in comparison to strangeness nuclei. She created a formula that can calculate the drip line Lambda-hypernuclei. Because of her interest, she joined our HKS collaboration at JLAB in summer of 2008 and will participate in all our hypernuclear physics experiments in Hall C that are currently approved. I believe that her addition to the collaboration will be beneficial to our program.

The HKS program, high precision mass spectroscopy of Lambda-hypernuclei with wide mass range, has completed its second phase experiment (E01-011/HKS) and its third phase experiment E05-115 (HKS/HES) will be carried out in 2009 (from March to October). Her addition to the collaboration will definitely strengthen our collaboration with stronger U.S. participation and contributions. Her group is in Richmond, almost local to JLAB, her experimental skills will help this large scale experiment that needs five months to install and to commission all the needed equipment and beam lines and two months to run. Her theoretical background and skill will enable her to contribute on the data analysis as well.

More importantly, Prof. Chhanda Samanta can eventually become a major player in the newly created hypernuclear physics program on decay pion spectroscopy from mesonic weak decay of Lambda-hypernuclei. Technically, the goal is to reach ~100 keV energy resolution and better than 30 keV binding energy precision so that the precision of ground state and low lying states that decay significantly through weak decay will be significantly better than emulsion data. There are two major scientific goals: (1) Provide precise measurement of the ground state of light Lambda- hypernuclei to check the basic YN interaction models which were previously established relying on less precise emulsion data; and (2) search for high exotic and highly neutron rich Lambda-hypernuclei such as $^6\Lambda H$ through the production of highly excited initial hypernuclear system followed by fragmentation to lighter hypernucleus then weak decay. The second goal is to study the maximum number of neutrons that are allowed for a Lambda- hypernuclei in comparison to exotic non-strange nuclei. The experiment E08-012 was conditionally approved by JLAB PAC33 with A- rating. The PAC recommended test run on the feasibility before 12 GeV upgrade shutdown. The collaboration is currently planning a parasitic run in Hall A after 2009. A general agreement was made with Hall A and currently we are studying one of the Hall A equipment, BigBite spectrometer, to confirm its capability for such test run. When BigBite study is completed, we will officially request this parasitic run to Hall A in December of 2008. The goal is to develop this new program to be carried out at the beginning

Fig 9. Letter of support from Dr. L. Tang, group leader of the hypernuclear collaboration.
of the 12 GeV period of CEBAF. Prof. Chhanda Samanta’s theoretical expertise and interest in this exotic hypernuclei field will help the establishment of the program since it is new and has never been done before.

Overall, I believe that Prof. Chhanda Samanta will strengthen our U.S. experimental hypernuclear physics field and will be an important collaborator in the hypernuclear physics at JLAB. Thus, I strongly recommend her to be supported.

Sincerely,

Liguang Tang

Professor of Physics
(757)269-6255
tangl@jlab.org

Fig 9 (continued). Letter of support from Dr. L. Tang, hypernuclear collaboration leader.
References


[56] W. Xu et al. PWIA extraction of the neutron magnetic form factor from quasi-elastic He-3(pol.)(e(pol.),e') at $Q^2 = 0.3 - (GeV/c)^2$ to 0.6 - (GeV/c)$^2$. Phys. Rev., C67:012201, 2003.


4 Publications Since Last Review

Refereed Journals

The first set of publications are ones where Gilfoyle had considerable input as author or Collaboration reviewer.


4. R. DeVita et al. (The CLAS Collaboration), ‘Search for the Θ$^+$ Pentaquark in the reactions $\gamma p \rightarrow K^0K^0\pi$ and $\gamma p \rightarrow K^-K^0\rho$', Phys. Rev. D. 74, 032001 (2006).


The second set below are publications where Gilfoyle had a standard contribution in terms of CLAS service work, offering suggestions during the comment period for the Collaboration review, etc.


Technical Reports


Proceedings (* denotes undergraduate co-author)


5 Principal Collaborators

I have worked with many members of the CLAS Collaboration over the years. A listing of the full collaboration is available at the following website.

http://www.jlab.org/Hall-B/general/phonebook.html

The list below includes members of the Collaboration that I have worked with closely over the last four years and others outside the Collaboration.

<table>
<thead>
<tr>
<th>Mac Mestayer</th>
<th>William Brooks</th>
<th>Bernhard Mecking</th>
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<tr>
<td>Lawrence Weinstein</td>
<td>Michael Vineyard</td>
<td>Andrei Afanasev</td>
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<td>David Jenkins</td>
<td>Jeffrey Lachniet</td>
<td>Latifa Elouadrhiri</td>
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<td>Sabine Jeschonnek</td>
<td>J.W. Van Orden</td>
<td>Hartmut Arenhövel</td>
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<td>John Arrington</td>
<td>Mark Ito</td>
<td>Eliot Wolin</td>
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<tr>
<td>Arne Freyberger</td>
<td>Kawtar Hafidi</td>
<td>Brian Quinn</td>
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The remaining members of the CLAS Collaboration are listed below.

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<thead>
<tr>
<th>A. Klimenko</th>
<th>S.E. Kuhn</th>
<th>P.E. Bosted</th>
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<tr>
<td>G.E. Dodge</td>
<td>T.A. Forest</td>
<td>Y. Prok</td>
<td>G. Adams</td>
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<td>P. Ambrozewicz</td>
<td>M. Anghinolfi</td>
<td>G. Asryan</td>
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<td>H. Bagdasaryan</td>
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<td>N.A. Baltzell</td>
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<td>I. Bedlinskiy</td>
<td>M. Bektasoglu</td>
<td>M. Bellis</td>
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<td>A.S. Biselli</td>
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<td>D. Branford</td>
<td>S. Buhlmann</td>
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<td>C. Butuceanu</td>
<td>J.R. Calarco</td>
<td>S.L. Careccia</td>
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<td>D.S. Carman</td>
<td>B. Carnahan</td>
<td>A. Cazes</td>
<td>S. Chen</td>
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<td>P.L. Cole</td>
<td>P. Collins</td>
<td>P. Coltharp</td>
<td>P. Corvisiero</td>
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<td>D. Crabb</td>
<td>H. Crannell</td>
<td>V. Crede</td>
<td>J.P. Cummings</td>
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<td>R. De Masi</td>
<td>R. DeVita</td>
<td>E. De Sanctis</td>
<td>P.V. Degtyarenko</td>
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<td>H. Denizli</td>
<td>L. Dennis</td>
<td>A. Deur</td>
<td>C. Djalali</td>
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<td>J. Donnelly</td>
<td>D. Doughty</td>
<td>P. Dragovitsch</td>
<td>M. Dugger</td>
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<td>S. Dytman</td>
<td>O.P. Dzyubak</td>
<td>H. Egiyan</td>
<td>P. Eugenio</td>
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<td>R. Fatemi</td>
<td>G. Fedotov</td>
<td>R.J. Feuerbach</td>
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<td>M. Garcon</td>
<td>G. Gavalian</td>
<td>K.L. Giovanetti</td>
<td>F.X. Girod</td>
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<td>J.T. Goetz</td>
<td>E. Golovatch</td>
<td>A. Gonenc</td>
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<td>K.A. Griffioen</td>
<td>M. Guidal</td>
<td>M. Gúllo</td>
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<td>L. Guo</td>
<td>V. Gyuriyan</td>
<td>C. Hadgidakis</td>
<td>K. Hafidi</td>
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<td>R.S. Hakobyan</td>
<td>J. Hardie</td>
<td>D. Heddle</td>
<td>F.W. Hersman</td>
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</table>
The members of the hypernuclear collaboration are listed below.

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<tr>
<th>Name</th>
<th>Institute/University</th>
<th>Name</th>
<th>Institute/University</th>
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<tr>
<td>A. Margaryan</td>
<td>Yerevan Physics Institute, Armenia</td>
<td>L. Tang</td>
<td>Hampton University, USA</td>
</tr>
<tr>
<td>O. Hashimoto</td>
<td>Tohoku University, Japan</td>
<td>J. Reinhold</td>
<td>Florida International University, USA</td>
</tr>
<tr>
<td>Ed. Hungerford</td>
<td>University of Houston, USA</td>
<td>M. Furic</td>
<td>University of Zagreb, Croatia</td>
</tr>
<tr>
<td>F. Garibaldi</td>
<td>Istituto Nazionale di Fisica Nucleare, Italy</td>
<td>S.N. Nakamura</td>
<td>Tohoku University, Japan</td>
</tr>
</tbody>
</table>
6 Biographical Sketch: Dr. Gerard P. Gilfoyle

Degrees
Ph.D., University of Pennsylvania, 1985 - ‘Resonant Structure in $^{13}$C($^{13}$C,$^4$He)$^{22}$Ne’, H.T. Fortune, adviser.

Experience
2008-present - Clarence E. Denoon Professor of Science, University of Richmond.
2004-present - Professor of Physics, University of Richmond.
1999-2000 - American Association for the Advancement of Science Defense Policy Fellow.
1993-2004 - Associate Professor of Physics, University of Richmond.
Summer, 1988 - Visiting Research Professor, University of Pennsylvania.
1987-1993 - Assistant Professor, University of Richmond.
1985-1987 - Postdoctoral Research Fellow, SUNY at Stony Brook.
1979-1985 - Research Assistant, University of Pennsylvania.

Research and Teaching
1990-present - US Department of Energy ($1,361,000$).
2002-2003 - SURA Sabbatical Support ($10,000$).
2002-2003 - Jefferson Laboratory Sabbatical Support ($28,335$).

Grants
2001-2002 - National Science Foundation ($175,000$).
1999-2000 - American Association for the Advancement of Science ($48,000$).
1995-1997 - National Science Foundation ($14,986$).

Selected Service
2006 - present - Chair, Nuclear Physics Working Group, CLAS Collaboration.
2006 - present - CLAS Coordinating Committee.
2005 - Reviewer, National Science Foundation (Nuclear Physics).
2003 - present - Southeastern Universities Research Association Trustee.
2002 - present - Reviewer, CLAS Collaboration.
2002 - Reviewer, Civilian Research and Development Foundation.
2000 - 2006 - Chair, Department of Physics.
1999 - Reviewer, Department of Energy EPSCoR Program.
1996 - Chair, review panel, National Science Foundation, Instrumentation and Laboratory Improvement Program.

Honors
2004 - Who’s Who Among America’s Teachers.
2003 - University of Richmond Distinguished Educator Award.
Phi Beta Kappa, 1978.
Selected Listing of Refereed Publications


Selected Presentations


7 Biographical Sketch: Dr. Chhanda Samanta

Degrees

Ph.D., University of Maryland, 1981 - 'A study of proton and alpha induced quasifree knockout reactions', N.S. Chant and Prof. P. G. Roos, advisors.
M.Sc., August 1971, University of Calcutta, INDIA.
B.Sc., August 1969, University of Calcutta, INDIA.

Experience

2007-present - Visiting Lecturer, University of Richmond.
2007-present - Sr. Professor H, Saha Institute Of Nuclear Physics.
2006-present - Affiliate Professor, Homi Bhabha National Institute, BARC, Mumbai.
2000-2008 - Affiliate Professor, Virginia Commonwealth University, Richmond, VA.
1995-1996 - C.O.E - Professor, RCNP, Osaka University, JAPAN.
1991-1996 - Associate Professor, Saha Institute of Nuclear Physics, INDIA.
1986-1991 - Reader, Saha Institute of Nuclear Physics, INDIA.
1986 - Visiting Scientist, University of Maryland, College Park, MD.
1985 - Visiting Scientist, Institut für Kernphysik, Karlsruhe, GERMANY.
1983-1986 - Lecturer, Saha Institute of Nuclear Physics, INDIA.
1982-1983 - Postdoctoral Fellow, Saha Institute of Nuclear Physics, INDIA.
1978-1981 - Research Assistant, University of Maryland, College Park, MD.
1976-1981 - Research Assistant, Goddard Space Flight Centre, Greenbelt, MD.
1975-1976 - Teaching Assistant, University of Maryland, College Park, MD.
1973-1974 - Teaching Assistant, University of Utah, Salt Lake City, Utah.

Honors

1998 - Yamada Science Foundation award, Japan.
2003 - Affiliate Professor, Virginia Commonwealth University, Richmond, Va.

Refereed Publications


4. P. Roy Chowdhury, C. Samanta and D. N. Basu ‘Nuclear lifetimes for alpha radioactivity of elements with 100¡Z¡130’ Nuclear Data and Atomic Data Tables (available online from March 2008).


8 Student Tracking Information

The University of Richmond is a primarily undergraduate institution and the Physics Department has no graduate students.
9 Discussion of Budget

9.1 Budget Justification

YEAR 1

A.1 Senior personnel’s summer salaries are 2/9’s of their academic year salaries or $13,500 whichever is smallest.

B.3 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. $1000 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at $0.42 per mile. Note: routine faculty travel of this sort is covered by the University.

2. $1000 - Lodging at the JLab residence facility ($55/night) during shifts for faculty and students and Collaboration meetings based on 12-16 shifts/yr and three Collaboration meetings of about 3 days/meeting.

3. $2000 - Additional travel expenses for invited talks. Over the last two years Gilfoyle and Samanta have been invited to give eight talks. There are some University funds for this travel, but they are limited and we have made heavy use of them in the last two years.

4. $7000 - Expenses for staying at the JLab residence facility for 32 weeks during a one-year sabbatical in 2009-2010. Based on four nights per week in the residence facility and one round trip from Richmond to JLab each week. We have subtracted the University’s contribution of support for ‘routine’ travel which consists of covering one round trip per week plus travel for shifts and CLAS Collaboration meetings.

Total = $11,000

F.1 - $1,500 - Computer parts and repair (e.g., office supplies, etc) for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.

YEAR 2

A.1 Senior personnel’s summer salaries are 2/9’s of their academic year salaries or $13,500 whichever is smallest.

B.3 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. $1000 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at $0.42 per mile. Note: routine faculty travel of this sort is covered by the University.

2. $1000 - Lodging at the JLab residence facility ($55/night) during shifts for faculty and students and Collaboration meetings based on 12-16 shifts/yr and three Collaboration meetings of about 3 days/meeting.
3. $2000 - Additional travel expenses for invited talks. Over the last two years Gilfoyle and Samanta have been invited to give eight talks. There are some University funds for this travel, but they are limited and we have made heavy use of them in the last two years.

Total = $4,000

F.1 - $1,500 - Computer parts and repair (e.g., office supplies, etc) for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.

YEAR 3

A.1 Senior personnel’s summer salaries are 2/9’s of their academic year salaries or $13,500 whichever is smallest.

B.4 Two undergraduate students per senior personnel for 10 summer weeks. This rate is the same as the University stipends. Includes 8.5% for fringe benefits.

D.1 Domestic travel:

1. $1000 - Round trip mileage charge for students to take shifts at JLab and attend Collaboration meetings. Based on 12-16 shifts per year and three Collaboration meetings of about 3 days/meeting. It is 150 miles round trip from the University of Richmond to JLab, at $0.42 per mile. Note: routine faculty travel of this sort is covered by the University.

2. $1000 - Lodging at the JLab residence facility ($55/night) during shifts for faculty and students and Collaboration meetings based on 12-16 shifts/yr and three Collaboration meetings of about 3 days/meeting.

3. $2000 - Additional travel expenses for invited talks. Over the last two years Gilfoyle and Samanta have been invited to give eight talks. There are some University funds for this travel, but they are limited and we have made heavy use of them in the last two years.

Total = $4,000

F.1 - $1,500 - Computer parts and repair (e.g., office supplies, etc) for our computing cluster and associated laboratory at Richmond and an office we have at JLab.

H.1 - Indirect costs: 52% of wages, salaries, and fringe benefits.
9.2 Current and Pending Support

We have no pending proposals at this time.

9.3 Anticipated Carryover

By the end of this proposal period we expect to have less than $1000 remaining.
Curriculum vitae
Gerard P. Gilfoyle

Degrees
Ph.D., University of Pennsylvania, 1985 - 'Resonant Structure in $^{13}$C($^{13}$C,$^{4}$He)$^{22}$Ne', H.T. Fortune, advisor.

Experience
2008-present - Clarence E. Denoon Professor of Science.
2004-present - Professor of Physics, University of Richmond.
1999-2000 - Defense Policy Fellow, American Association for the Advancement of Science.
1993-present - Associate Professor of Physics, University of Richmond.
Summer, 1988 - Visiting Research Professor, University of Pennsylvania.
1987-1993 - Assistant Professor, University of Richmond.
1985-1987 - Postdoctoral Research Fellow, SUNY at Stony Brook.
1979-1985 - Research Assistant, University of Pennsylvania.

Research and Teaching
2007-2009 - Department of Energy ($60,000).
2002-2003 - SURA Sabbatical Support ($10,000).
2002-2003 - Jefferson Laboratory Sabbatical Support ($28,335).
2002-2005 - Department of Energy ($225,000).
2001-2002 - National Science Foundation ($175,000).
1999-2002 - Department of Energy ($222,000).
1996-1999 - Department of Energy ($300,000).
1995-1997 - National Science Foundation (teaching, $14,986).
1994-1995 - CEBAF Sabbatical Support ($24,200)
1993-1996 - Department of Energy ($284,000).
1990-1993 - Department of Energy ($287,000).

Service
2007-present - Richmond Science Scholars Committee.
2006-present - CLAS Coordinating Committee (manages 300-member CLAS Collaboration at Jefferson Lab).
2006-present - Chair, Nuclear Physics Working Group of the CLAS Collaboration.
2005-present - Reviewer for SURA Graduates Fellowship.
2003-present - Southeastern Universities Research Association Trustee.
2002-present - Reviewer, CLAS Collaboration.
2002 - Reviewer, Civilian Research and Development Foundation.
2000-2006 - Chair, Department of Physics.
Service
1993-1999, 2001 - Ethyl and Oldham Scholarship Committees
1999 - Reviewer, Department of Energy EPSCoR Program.
1997 - Chair, Jefferson Laboratory CLAS Collaboration nominating committee.
1996 - Chair, review panel, National Science Foundation, ILI Program.
1996-1998 - Managed the Physics Department’s high school outreach program.

Honors
2004 Who’s Who Among America’s Teachers.
2003 University of Richmond Distinguished Educator Award.
Sigma Chi Educator of the Month Award, March, 1990.
Academic All-American in football, 1979.
Phi Beta Kappa, 1978.

Courses Taught
- Introductory physics with Calculus 1-2
- Quantum mechanics 1-2
- Algebra-based introductory physics 1-2
- Classical mechanics
- Liberal arts physics 1-2
- Statistical mechanics
- Intermediate laboratory
- Computational methods in physics
- Senior Seminar
- Junior Seminar

Selected Listing of Refereed Publications


Selected Presentations


3. “Hunting For Faculty Jobs”, Panel on academic careers at the headquarters of the American Association for the Advancement of Science, December 6, 2007.


Refereed Publications


Other Publications


Invited Talks and Panels


5. “Hunting For Faculty Jobs”, Panel on academic careers at the headquarters of the American Association for the Advancement of Science, December 6, 2007.

6. “Science and Security in an Age of Terrorism”, talk presented to the Brandermill/Midlothian/Wood Lake Lion’s Club, University of Richmond, November 8, 2007.


8. “Nuclear Physics at the University of Richmond”, American School of Antananarivo, Antananarivo, Madagascar, September 13, 2007.


30. ‘The September 11 Attacks’, interviewed by local TV station (Channel 12) to discuss the September 11 attacks, Sep 11, 2001.


33. ‘The Dale Earnhardt Crash’, interviewed by local TV station (Channel 6) to discuss the physics behind Dale Earnhardt’s fatal crash in the Daytona 500, Feb. 22, 2001.

34. ‘Using Nuclear Materials to Prevent Nuclear Proliferation’, colloquium presented at Old Dominion University, Norfolk, VA, Nov. 3, 2000.

35. ‘Using Nuclear Materials to Prevent Nuclear Proliferation’, seminar presented at the University of Richmond, September 19, 2000.


37. ‘New Tools and Opportunities for Preventing Nuclear Use and Proliferation’, invited talk presented to Dr. Hans Mark, Director of Defense Research and Development, the Pentagon, May 12, 2000.


42. ‘Undergraduate Research in the Natural Sciences at the University of Richmond’, talk presented at the University of Richmond Board of Trustees dinner, September 30, 1999.


44. ‘The EPR Paradox’, presented to the University of Richmond Physics Department, March 6, 1997.


46. ‘The Limits to Nuclear Fusion of the $^{16}O+^{27}Al$ System’, presented to the Department of Physics, Virginia Commonwealth University, November 15, 1990.
47. ‘The Limits to Nuclear Fusion of the $^{16}$O+$^{27}$Al System’, presented to the Department of Physics, George Washington University, April, 1990.

48. ‘Incomplete Fusion Reactions in the $^{16}$O+$^{27}$Al System’, presented to the Department of Physics, University of Richmond, February 7, 1987.

49. ‘Incomplete Fusion Reactions in the $^{16}$O+$^{27}$Al System’, presented to the Department of Physics, Yale University, January 21, 1987.

50. ‘Incomplete Fusion Reactions in the $^{16}$O+$^{27}$Al System’, presented to the Department of Physics, Rutgers University, October 5, 1986.

51. ‘Quasimolecular States in the $^{13}$C+$^{12}$C System’, presented to the Department of Physics, University of Pennsylvania, September 14, 1985.

52. ‘Quasimolecular States in the $^{13}$C+$^{12}$C System’, presented to the Department of Physics, SUNY at Stony Brook, April 25, 1985.

53. ‘Quasimolecular States in the $^{13}$C+$^{12}$C System’, presented to the Department of Physics, Franklin and Marshall College, March 11, 1985.

Abstracts of Presentations at National and International Meetings


95


Jefferson Laboratory Technical Reports


Jefferson Laboratory Talks and Presentations


Projects Managed for the US Department of Defense (dates show completion).


Independent Undergraduate Research Projects Directed

- * - indicates projects that were presented at national or international meetings.
- ** - indicates projects that also received travel funds to attend those meetings from the American Physical Society.

1. ‘Precision of the $G_{M}^{n}$ Measurement at high $Q^{2}$’, Mark Moog, summer, 2008.**
3. ‘Systematic Uncertainties in $A_{LT}'$ for $D(e',e'p)n'$, Matt Jordan, summer, 2008.**
7. ‘Simulations of CLAS for the $\cos(2\phi_{pq})$ analysis’, Kuri Gill, summer and fall, 2007.**
8. ‘Scientific Advice to the House: Who Has the Congressional Ear?’, Kristen Greenholt, senior thesis in Political Science with Dr. D. Palazzolo and Dr. P. Smallwood, April, 2007.
9. ‘Extracting the Fifth Structure Function and Hadronic Fiducial Cuts for the CLAS E5 Data Run at Jefferson Laboratory’, Kristen Greenholt, senior thesis in Physics, winner of the Taylor award for best Senior Seminar, April, 2007.
10. ‘Extracting the Fifth Structure Function and Hadronic Fiducial Cuts for the CLAS E5 Data Run’, Kristen Greenholt, summer 2006.**
11. ‘CLAS Simulations for the E5 Data Set’, Rusty Burrell, senior thesis in Physics, April, 2007 and summer 2006.**
12. ‘Extracting the Fifth Structure Function and Electron Fiducial Cuts for the CLAS E5 Data Run’, Kristen Greenholt, summer, 2004.**
17. ‘From Quarks to Nucleons’, F. Chinchilla, summer, 2001.*

*The projects listed in this section were performed during summer fellowships or as independent, academic-year investigations or both.
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<th>No.</th>
<th>Title</th>
<th>Author</th>
<th>Date</th>
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<tr>
<td>18</td>
<td>‘Analysis of Electron Scattering Data From the CLAS’</td>
<td>Adam Weaver</td>
<td>2001</td>
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<td>21</td>
<td>‘Elastic Peak Monitoring for the CLAS’</td>
<td>David Vermette</td>
<td>2000</td>
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<td>23</td>
<td>‘Determining the Maximum Drift Time of the CLAS’</td>
<td>Danielle Clement</td>
<td>1998</td>
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<td>‘Simulation of f0(980) Production in the CLAS’</td>
<td>Hong-Ying Lan</td>
<td>1997-1998</td>
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<td>25</td>
<td>‘Spatial Resolution of the Nose Cone Prototype Drift Chamber’</td>
<td>Steven Levy</td>
<td>1996</td>
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<td>26</td>
<td>‘Tests of Drift Velocity Algorithm Speeds’</td>
<td>Yaw Opoku</td>
<td>1996</td>
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<td>‘A Graphical User Interface for the CLAS Drift Chamber Calibration Software’</td>
<td>Hong-Ying Lan</td>
<td>1996</td>
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<td>28</td>
<td>‘Drift Velocity Calibration for the CLAS Drift Chamber System’</td>
<td>Steven Levy</td>
<td>1995-1996</td>
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<td>29</td>
<td>‘Statistical Analysis of the 12C + 13 C System’</td>
<td>M.Nimchek</td>
<td>summer 1994</td>
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<td>31</td>
<td>‘Light Particles Produced in Central Collisions Between 40Ca and 12C Nuclei’</td>
<td>J.H.Rollinson</td>
<td>summer 1991</td>
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<td>32</td>
<td>‘A Computer Simulation of a Nuclear Fusion Reaction for Evaporation Residues’</td>
<td>Craig Gosdin</td>
<td>1990</td>
</tr>
<tr>
<td>33</td>
<td>‘Measuring Cross Sections From the 12C(13C, α)21Ne Reaction’</td>
<td>C.Cardounel</td>
<td>1990-1991</td>
</tr>
<tr>
<td>35</td>
<td>‘Analysis of the 12C+13C Reaction’</td>
<td>S.Sigworth</td>
<td>1989</td>
</tr>
<tr>
<td>36</td>
<td>‘A Computer Simulation of a Nuclear Fusion Reaction for Evaporation Residues’</td>
<td>Craig Gosdin</td>
<td>1988</td>
</tr>
<tr>
<td>37</td>
<td>‘Analysis of the 12C(13C, α)21Ne Reaction’</td>
<td>M.Simpson</td>
<td>1988</td>
</tr>
<tr>
<td>38</td>
<td>‘Analysis of the 13C(13C, α)21Ne Reaction’</td>
<td>J.Richards</td>
<td>1984</td>
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</tbody>
</table>

**Presentations at the University of Richmond Student Symposium**

Remaining University and Professional Service (see pages 81-82 for highlights)

1. 2007-present - Member of the Environmental Awareness Group.
2. 2006-present - Organized Physics outreach program called Deconstruction Night.
3. 2006-present - Physics webpage manager.
4. 2004-present - Faculty advisor to the Richmond Physics Olympics.
5. 2005 - Wrote and developed the Physics assessment plan.
6. 2005 - Chair of mid-course review for Dr. Ted Bunn.
7. 2004 - Member of the local organizing committee for PN12, the Physics of Nuclei at 12 GeV held at Newport News, VA, Nov 1-5, 2004.
8. 2004-2005 - Chair of Physics faculty search committee (two tenure-track appointments, one laboratory director, and one administrative assistant).
10. 2004 - Chair of mid-course review for Dr. Mirela Fetea.
11. 2003-2004 - Chair of Physics faculty search committee (one laboratory director).
12. 2002-2003 - Chair of Physics faculty search committee (one adjunct faculty appointment).
14. 2004 - Chair of promotion review for Dr. Michael Vineyard.
15. 2001-2002 - Chair of Physics faculty search committee (one tenure-track appointment).
16. 2001 - Managed Physics Department review by Research Corporation.
17. 2000-present - University Science Review Committee.
18. 2000-present - Represented Physics at Prospective Student Open House and Majors’ Fair.
22. 1999, 2001-2002 - Physics Department’s high school outreach program.
24. 1997 - Chair, Jefferson Laboratory CLAS Collaboration nominating committee.
25. 1998-1999 - Chair, Science Initiative curriculum sub-committee.
34. 1993-1996 - Honors Committee.
35. 1993-1994 - Dean of Arts and Sciences ad hoc Committee on Evaluations.
37. 1991-present - Undeclared Student Advisor (except during leave).