Medium Energy Nuclear Physics Research at the University of Richmond

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Contents

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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.

1 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.

Title	Label
Measurement of the Neutron Magnetic Form Factor at High Q^2 Using the Ratio Method on Deuterium (Gilfoyle: spokesperson and contact person)	E12-07-104
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	E94-017
Out-of-Plane Measurements of the Structure Functions of the Deuteron (Gilfoyle: spokesperson)	CLAS-Approved Analysis[1]
Quark Propagation and Hadron Formation (Gilfoyle: co-spokesperson)	E12-06-117
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)	E05-115/E08-002
Study of Light Hypernuclei by Pionic Decay at JLab	E08-012

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 2.1.1). 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].[2] We are leading the effort to publish a paper on this work. A draft

[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.

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^n to higher Q^2 as part of the JLab 12-GeV Upgrade (Section 2.1.1). 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 extract G_M^n. We have copied the data to the Richmond computing cluster and completed initial calibrations, efficiency measurements, *etc.* (Section 2.1.1).

We have made progress in our analysis of the fifth structure function in $^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$ (Section 2.1.2). This project is a CLAS Approved Analysis.[1] 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 2.1.4). Gilfoyle continues to serve as chair of the Nuclear Physics Working Group and on the CLAS Coordinating Committee (Section 2.1.5). 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 2.2.1). We will complete the analysis of the fifth structure function in quasielastic kinematics for the reaction $^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$. 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 2.2.2). 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 2.2.4).

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 2.2.6, 2.2.7, 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.

2 Project Description

2.1 Status of Current Projects

2.1.1 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 σ_{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 θ 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

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

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 θ_{pq}^{max}, the maximum angle between the nucleon direction and the three-momentum transfer $\vec{q}$, 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 2.2.1). The data are plotted as the ratio to $G_M^n/\mu_n G_D$ where μ_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.Lachniet's thesis (a CMU graduate student) [1].[2] The Richmond group have taken over primary responsibility for completing the work since spring 2008 after J.D.Lachniet 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,

[2]CLAS Collaboration rules require a separate technical paper to be reviewed by an internal committee before the process of publication begins.

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.

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].

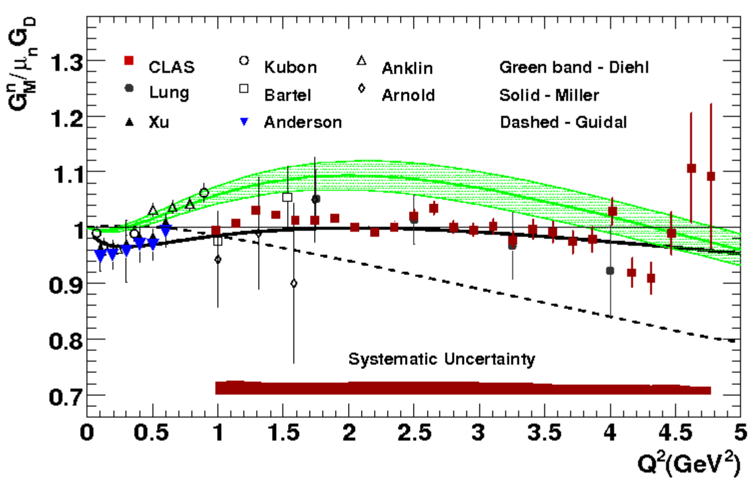

Figure 1: Selected results for $G_M^n/(\mu_n G_D)$ from the CLAS measurement are compared with a selection of previous data [25, 26, 27, 28, 29, 30, 31] and theoretical calculations [32, 33, 34, 35]

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_M^n 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.

2.1.2 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

$$\frac{d\sigma^5}{d\nu d\Omega_e d\Omega_{pq}} = \sigma_L + \sigma_T + \sigma_{TT}\cos\phi_{pq} + \sigma_{LT}\cos 2\phi_{pq} + h\sigma'_{LT}\sin\phi_{pq} \quad (3)$$

where the σ_i are the different components of the cross section, $h = \pm 1$ is the helicity of the electron beam, and ϕ_{pq} is the azimuthal angle of the ejected proton relative to the 3-momentum transfer $\vec{q}$. This angle ϕ_{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 ϕ_{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.

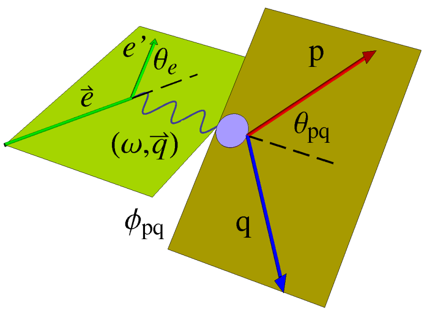

Figure 2: Kinematics of $D(\vec{e}, e'p)n$.

In this status report we focus on our progress extracting the fifth structure function σ'_{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 σ_{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

$$\langle \sin\phi_{pq}\rangle_\pm = \frac{\int_0^{2\pi} \sigma^\pm \sin\phi_{pq} d\phi_{pq}}{\int_0^{2\pi} \sigma^\pm d\phi_{pq}} = \frac{1}{N_\pm}\sum_{i=1}^{N_\pm} \sin\phi_i = \pm\frac{A'_{LT}}{2} \quad (4)$$

where the pluses and minuses refer to the beam helicity, $\sigma^\pm$ is the cross section in Equation 3 for different beam helicities, ϕ_i is ϕ_{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 2.1.1. 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 $Q^2 = 0.2 - 2.0$ $(\mathrm{GeV/c})^2$. 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.

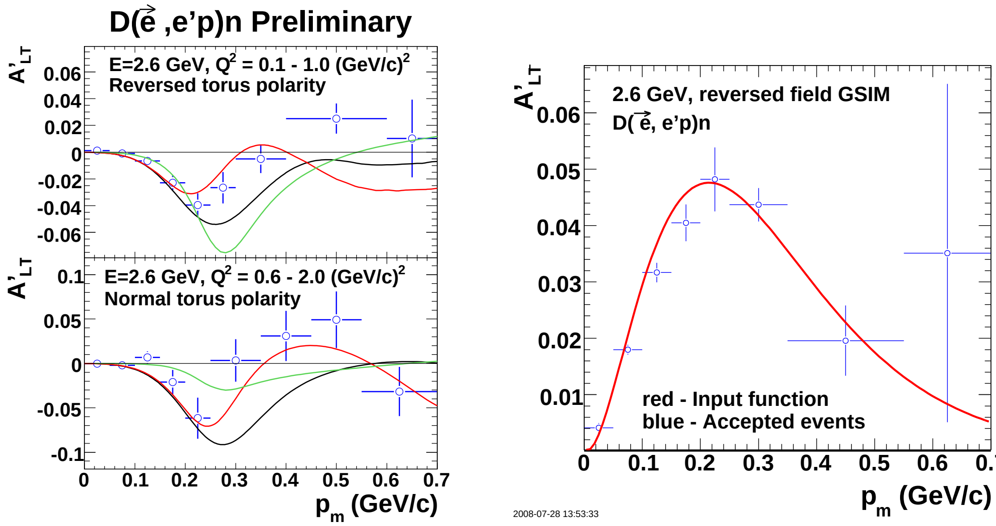

Figure 3: Preliminary results for the asymmetry A'_{LT} for the 2.6-GeV, E5 data sets (left-hand panel). Curves are discussed in the Section 2.2.2. The right-hand panel is a comparison of user inputs and simulation results for the 2.6-GeV, reversed torus polarity data.

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 $Q^2 = 1.1$ GeV^2 (lower panel) and $Q^2 = 0.7$ 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 NN 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 $p_m < 0.4$ 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[1] (see Table 1) and Gilfoyle is the spokesperson. Preliminary results have been presented at conferences [5] and a CLAS analysis note is in preparation.

2.1.3 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 π^0, η, and η' exit channels. This future experiment and E12-07-104 (the 12-GeV G_M^n measurement) have motivated our interest in the detection of neutral particles as part of the CLAS12 software development and the 12-GeV Upgrade.

2.1.4 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.

2.1.5 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].

2.2 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

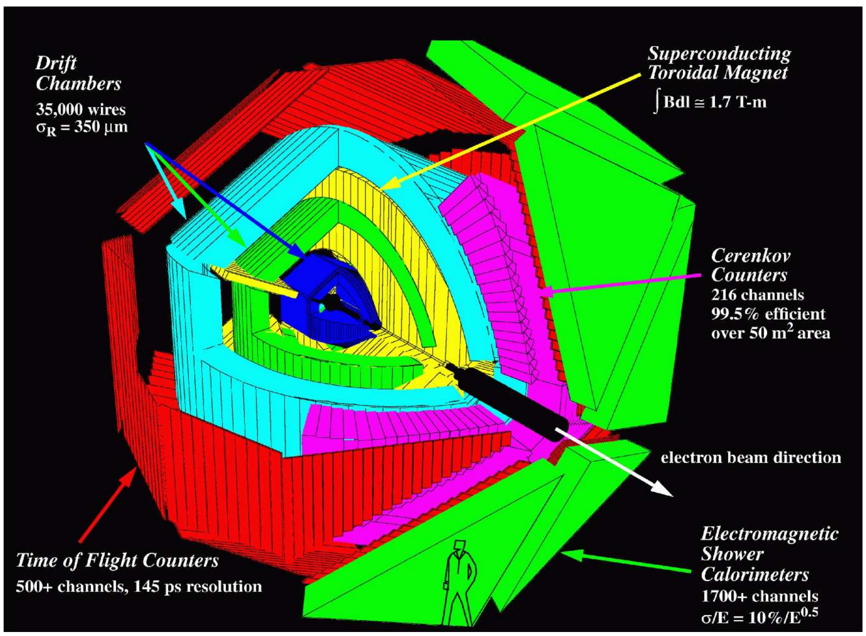

Figure 4: The CLAS detector.

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

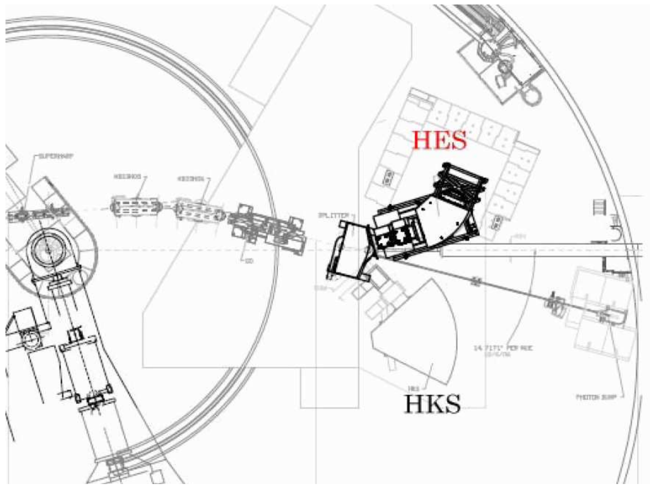

Figure 5: The HKS and HES in Hall C.

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.

2.2.1 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_M^n 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_M^n 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_M^n 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_M^n at lower Q^2 is shown in Figure 1 in Section 2.1.1 where G_M^n 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 Δ 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 $^3\vec{\mathrm{He}}(\vec{e}, e')$ reaction in concert with theoretical calculations to extract G_M^n [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. 2.1.1 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. 2.1.1) 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 *at 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 2.1.1 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^p and G_M^p from Bates [37], of G_E^n from Mainz [55], and of G_M^n 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 2.1.1 which shows that knowledge of R, nuclear correction factors $a(E, Q^2, \theta_{pq}^{max}, W_{max}^2)$, and the other elastic, nucleon form factors will enable us to extract G_M^n. To determine G_M^n we calculate the corrections $a(E, Q^2, \theta_{pq}^{max}, W_{max}^2)$ in Equation 2 with existing models [22]. The proton form factors are precisely known and the neutron's electric form factor G_E^n 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 $ep \to e'\pi^+ n$ 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 ep 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 θ_{pq} the angle between the detected nucleon and 3-momentum transfer $\vec{q}$ 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 2.1.2 and below) are from the same dataset so we can make efficient use of our time and resources.

2.2.2 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 nuclei. 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 2.1.2 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 2.1.2 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-4π solid angle of CLAS coupled with the high-quality, polarized beams at JLab create an inviting opportunity to study σ'_{LT}, σ_{LT}, and σ_{TT} (see Eq. 3). These structure functions depend on ϕ_{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 ν.

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 ν 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

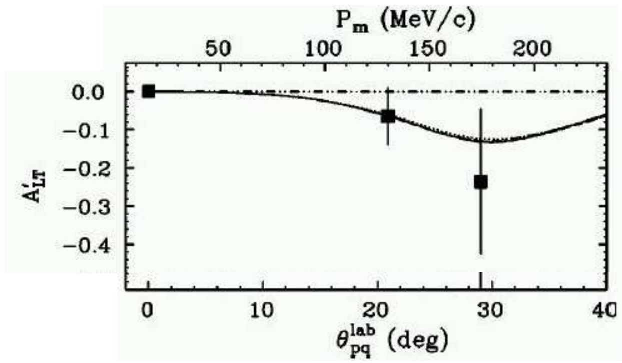

Figure 6: Measurements of A'_{LT} from Reference [65] at $Q^2 = 0.13$ (GeV/c)^2.

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 ν [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 ν [66].

We have been working with several theory groups which we discussed in Section 2.1.2. 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

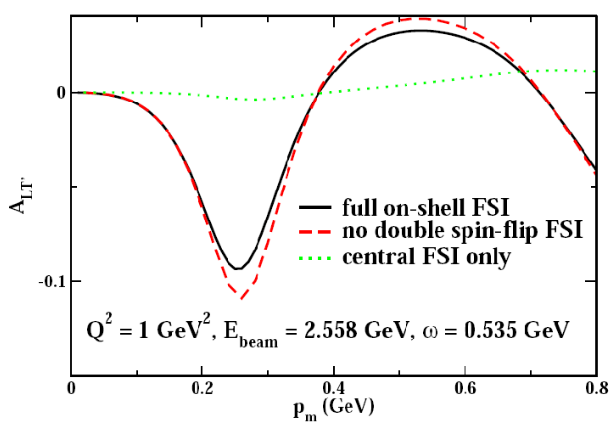

Figure 7: Effect of spin-orbit FSI forces calculated in Ref. [71].

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 σ'_{LT} results and move on to the other two structure functions σ_{LT} and σ_{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, ϕ_{pq}-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.

2.2.3 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 π^0, η, and η' 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 2.2.4.

2.2.4 CLAS12 Simulation (*Gilfoyle*)

We now discuss our plans to support the completion of the 12-GeV CEBAF Upgrade at JLab [16] mentioned in Section 2.2. 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 ≈ 10 Hz for the simulation versus ≈ 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 $Q^2 = 14$ GeV^2 (see Sections 2.1.1 and 2.2.1). 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

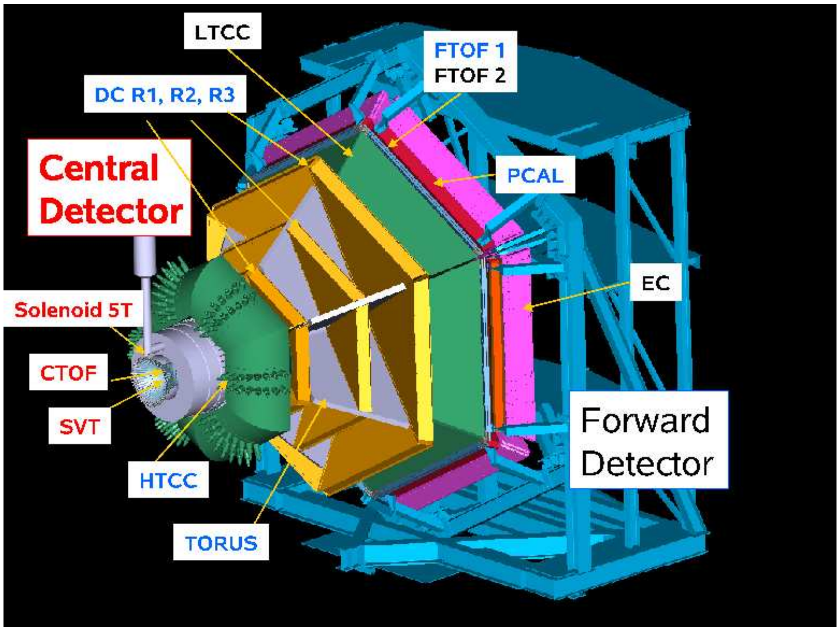

Figure 8: The CLAS12 detector in Hall B.

E12-06-117 will focus on the physics of quarks moving through nuclear matter and how they evolve to fully-formed hadrons (see Sections 2.1.3 and 2.2.3). Our responsibilities are to study the electroproduction of π^0, η, and $\eta\prime$ 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 η in the η' decay will also be detected via its 2γ decay. Detection will 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 π^0 and η 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^2 G_M^n data (see Section 2.2.1).

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]).

2.2.5 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.

2.2.6 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 2.2.7). 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 A$^-$ 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 A$^-$ 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 hypernculei. 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 $\Sigma - \Lambda$ 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]:

$$\begin{aligned} B(A,Z) =&15.777A - 18.34A^{2/3} - 0.71\frac{Z(Z-1)}{A^{1/3}} - \frac{23.21(N-Z_c)^2}{(1+e^{-A/17})A} + (1-e^{-A/30})\delta + \\ &n_Y[0.0335(m_Y) - 26.7 - 48.7|S|A^{-2/3}] \end{aligned} \quad (5)$$

where $\delta = 12A^{-1/2}$ for N, Z_c even, $\delta = -12A^{-1/2}$ for N, Z_c 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 $A = N + Z_c + n_Y$ is equal to the total number of baryons. N and Z_c are the number of neutrons and protons respectively while the Z in Eq. 5 is given by $Z = Z_c + n_Y q$ 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 δ 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 ${}^{13}_{\Lambda}$C, $\delta = +12A^{-1/2}$ as the (N, Z_c) combination is even-even, whereas, for non-strange normal ^{13}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 $S_Y = B(A,Z)_{hyper} - B(A - n_Y, Z_c)_{core}$ 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},Λ). 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 ΛN interaction is much weaker than the nucleon-nucleon interaction; 3) the ΛN 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 Λ hypernuclei is essential for the experimental projects undertaken at JLab.

A central ΛN potential has been found on the basis of an analysis of the binding energies of 1s shell hypernuclei and Λp scattering [94]. Within the exprerimental 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 Λp scattering. Within the Λ plus core model, the potential VΛN 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.

2.2.7 Faculty Researcher (*Samanta*)

As discussed in Section 2.2.6 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 2.2.6. 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 2.2.6. 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.

2.3 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.

2.4 Institutional Support and Resources

2.4.1 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 2.3 had travel support from the University and the American Physical Society in some cases. The University also supports routine faculty travel to JLab at the level of ≈$2,500 per year.

2.4.2 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^n 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.

2.4.3 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.

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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,

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

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4 Publications Since Last Review

Refereed Journals

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

1. J. Lachniet, A. Afanasev, H. Arenhvel, W.K. Brooks, G.P. Gilfoyle, S. Jeschonnek, B. Quinn, M.F. Vineyard, et al (the CLAS Collaboration), 'A Precise Measurement of the Neutron Magnetic Form Factor G_M^n in the Few-GeV^2 Region', arXiv:0811.1716v1 [nucl-ex], submitted to Physical Review Letters.

2. R. Nasseripour *et al.* (The CLAS Collaboration), 'Search for Medium Modifications of the rho meson', Phys. Rev. Lett. **99**, 262302 (2007).

3. K.Sh. Egiyan, G.A. Asryan, N.B. Dashyan, N.G. Gevorgyan, J.-M. Laget, K. Griffioen, S. Kuhn, *et al.* (The CLAS Collaboration), 'Study of Exclusive d(e,e'p)n Reaction Mechanism at High Q2', Phys. Rev. Lett. **98**, 262502 (2007).

4. R. DeVita *et al.* (The CLAS Collaboration), 'Search for the Θ^+ Pentaquark in the reactions $\gamma p \to \bar{K^0} K^+ n$ and $\gamma p \to \bar{K}0 K^0 p$', Phys. Rev. D. **74**, 032001 (2006).

5. K. Egiyan, *et al.* (The CLAS Collaboration), 'Measurement of 2- and 3-nucleon short range correlation probabilities in nuclei', Phys. Rev. Lett. **96**, 082501 (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.*

1. F.X. Girod *et al.* (The CLAS Collaboration), 'Deeply Virtual Compton Scattering Beam-Spin Asymmetries', Phys. Rev. Lett. **100**, 162002 (2008).

2. R. De Masi *et al.* (The CLAS Collaboration), 'Beam spin asymmetry in deep and exclusive ρ_0 electroproduction', Phys. Rev. C **77**, 042201 (2008).

3. D. G. Ireland *et al.* (The CLAS Collaboration), 'A Bayesian analysis of pentaquark signals from CLAS data', Phys. Rev. Lett. **100**, 052001 (2008).

4. K. Park *et al.* (The CLAS Collaboration), 'Cross Sections and Beam Asymmetries for ep→enπ^+ in the Nucleon Resonance Region of 1.7 < Q^2 < 4.5 GeV^2', Phys. Rev. C. **77**, 015208 (2008).

5. T. Mibe *et al.* (The CLAS Collaboration), 'Coherent Phi Meson Photoproduction from the Deuteron at Low Energies', Phys. Rev. C **76**, 052202 (2007).

6. M. Dugger *et al.* (The CLAS Collaboration), 'ρ_0 photoproduction on the proton for photon energies from 0.675 to 2.875 GeV', Phys. Rev. C **76**, 025211 (2007).

7. L. Guo *et al.* (The CLAS Collaboration), 'Cascade Production in the Reaction $\gamma p \to K^+ K^+ X$ and $\gamma p \to K^+ K^+ p^- X$', Phys. Rev. C **76**, 025208 (2007).

8. H. Denizli, S. Dytman, J. Mueller, *et al.* (The CLAS Collaboration), 'Q^2 Dependence of the S$_{11}$(1535) Photocoupling and Evidence for a P-wave resonance in eta electroproduction', Phys. Rev. C **76**, 015204 (2007).

9. I. Hleiqawi, K. Hicks, D. Carman, T. Mibe, G. Niculescu, A. Tkabladze, *et al.* (The CLAS Collaboration), 'Cross sections for the $\gamma p \rightarrow K*0\Sigma^+$ Reaction at E(γ) = 1.7 - 3.0 GeV', Phys. Rev. C **75**, 042201 (2007).

10. R. Bradford, R. Schumacher, *et al.* (The CLAS Collaboration), 'First Measurement of Beam-Recoil Observables C_x and C_z in Hyperon Photoproduction', Phys. Rev. C **75**, 035205 (2007).

11. P. Ambrozewicz, D.S. Carman, R. Feuerbach, M.D. Mestayer, B.A. Raue, R. Schumacher, A. Tkabladze, *et al.* (The CLAS Collaboration), 'Separated Structure Functions for the Exclusive Electroproduction of $K^+\Lambda$ and $K^+\Sigma_0$ Final States', Phys. Rev. C **75**, 045203 (2007).

12. P.E. Bosted, K.V.Dharmawardane, G.E. Dodge, T.A. Forest, S.E. Kuhn, Y. Prok, *et al.* (The CLAS Collaboration), 'Quark-Hadron Duality in Spin Structure Functions g1p and g1d', Phys. Rev. C **75**, 035203 (2007).

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14. K.V. Dharmawardane, P. Bosted, S.E. Kuhn, Y. Prok, *et al.* (The CLAS Collaboration), ' Measurement of the x- and Q^2-dependence of the spin asymmetry A1 of the nucleon', Phys. Lett. B **641**, 11 (2006).

15. S. Chen, H. Avakian, V. Burkert, P. Eugenio, *et al.* (The CLAS Collaboration), 'Measurement of Deeply Virtual Compton Scattering with a Polarized Proton Target', Phys. Rev. Lett. **97**, 072002 (2006).

16. S. Niccolai, M. Mirazita, P. Rossi, *et al.* (The CLAS Collaboration), 'Search for the Θ^+ pentaquark in the $\gamma d \rightarrow \Lambda n K^+$ reaction measured with CLAS', Phys. Rev. Lett. **97**, 032001 (2006).

17. B. McKinnon, K. Hicks, *et al.* (The CLAS Collaboration), 'Search for the Θ^+ pentaquark in the reaction $\gamma d \rightarrow pK^-K^+n$', Phys. Rev. Lett. **96**, 212001 (2006).

18. H. Egiyan, V. Burkert, *et al.* (The CLAS Collaboration), 'Single π^+ electroproduction on the proton in the first and second resonance regions at 0.25 GeV^2 $<$ Q^2 $<$ 0.65 GeV^2 using CLAS', Phys. Rev. C **73**, 025204 (2006).

19. R. Bradford, R. Schumacher, *et al.* (The CLAS Collaboration), 'Differential cross sections for $\gamma + p \rightarrow K^+ + Y$ for Λ and Σ_0 hyperons', Phys. Rev. C **73**, 035202 (2006).

20. M. Dugger, B. Ritchie, *et al.* (The CLAS Collaboration), 'Eta-prime photoproduction on the proton for photon energies from 1.527 to 2.227 GeV', Phys. Rev. Lett. **96**, 062001 (2006).

Technical Reports

1. J.D. Lachniet, W.K. Brooks, G.P. Gilfoyle, B. Quinn, and M.F. Vineyard. 'A high precision measurement of the neutron magnetic form factor using the CLAS detector', CLAS Analysis Note 2008-103, Jefferson Lab, 2008.
2. G.P.Gilfoyle, 'CLAS12 Event Reconstruction Overview', presented at the Hall B, 12 GeV Upgrade Workshop, May 14-15, 2007, Jefferson Lab.
3. G.P.Gilfoyle, 'Software Report', presented at the Hall B, 12 GeV Upgrade Workshop, May 14-15, 2007, Jefferson Lab.
4. G.P.Gilfoyle and V.Mokeev, 'Baryon Form Factors', update of the CLAS Conceptual Design Report, `http://www.jlab.org/Hall-B/clas12/Physics/Baryon/Baryon.pdf`, March, 2007, last accessed April 28, 2008.
5. L.B.Weinstein, G.P.Gilfoyle, F.J.Klein, 'Charged Particle Tracking in CLAS12', report of the internal CLAS Collaboration review committee, Feb., 2007.

Proceedings (denotes undergraduate co-author)*

1. G.P. Gilfoyle, *et al.*, (the CLAS Collaboration), 'Review of QCD Processes in Nuclear matter at Jefferson Lab', XVI International Workshop on Deep-Inelastic Scattering and Related Subjects, April 7-12, 2008, London, to be published in the DIS2008 proceedings.
2. G.P.Gilfoyle, 'Hunting for quarks', presented at the Conference Experience for Undergraduates, Division of Nuclear Physics meeting, Fall, 2008, Newport News, VA.
3. G.P. Gilfoyle, *et al.*, (the CLAS Collaboration), 'Measuring form Factors and Structure Functions with CLAS', Proceedings of the Third High-Energy Physics International Conference (HEP-MAD07), SLAC eConf C0709107, 2008.
4. G.P. Gilfoyle, *et al.*, (the CLAS Collaboration), 'A Precise Measurement of the Neutron Magnetic Form Factor G_M^n in the Few-GeV^2 Region', Exclusive Reactions at High Momentum Transfer, World Scientific, 2008.
5. M.Jordan* and G.P.Gilfoyle, 'Analysis of Out-of-Plane Measurements of the Fifth Structure Function of the Deuteron', Bull. Am. Phys. Soc., Fall DNP Meeting, DF.00009 (2208).
6. M.Moog* and G.P.Gilfoyle, 'Study of Inelastic Background for Quasielastic Scattering from Deuterium at 11 GeV', Bull. Am. Phys. Soc., Fall DNP Meeting, DF.00068 (2008).
7. G.P.Gilfoyle, 'Measuring the Fifth Structure Function in $D(\vec{e}, e'p)n$', poster presented at the Gordon Conference on Photonuclear Reactions, Tilton, NH, August 12, 2008.
8. K.Dirgachev* and G.P.Gilfoyle, 'CLAS 12 Simulation Analysis and Optimization', Bull. Am. Phys. Soc., Fall DNP Meeting, DA.00019 (2007).
9. E.F. Bunn, C.W. Beausang, M. Fetea, G. Gilfoyle, O. Lipan, M. Trawick, J. Mable, and J. Wimbush, 'The Richmond Physics Olympics', American Association of Physics Teachers meeting, Greensboro, NC, August, 2007.

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.

Mac Mestayer	William Brooks	Bernhard Mecking
Lawrence Weinstein	Michael Vineyard	Andrei Afanasev
David Jenkins	Jeffrey Lachniet	Latifa Elouadrhiri
Sabine Jeschonnek	J.W. Van Orden	Hartmuth Arenhövel
John Arrington	Mark Ito	Eliot Wolin
Arne Freyberger	Kawtar Hafidi	Brian Quinn

The remaining members of the CLAS Collaboration are listed below.

A. Klimenko	S.E. Kuhn	P.E. Bosted	K.V. Dharmawardane
G.E. Dodge	T.A. Forest	Y. Prok	G. Adams
M. Amarian	P. Ambrozewicz	M. Anghinolfi	G. Asryan
H. Avakian	H. Bagdasaryan	N. Baillie	J.P. Ball
N.A. Baltzell	S. Barrow	V. Batourine	M. Battaglieri
K. Beard	I. Bedlinskiy	M. Bektasoglu	M. Bellis
N. Benmouna	A.S. Biselli	B.E. Bonner	S. Bouchigny
S. Boiarinov	R. Bradford	D. Branford	S. Buhltmann
V.D. Burkert	C. Butuceanu	J.R. Calarco	S.L. Careccia
D.S. Carman	B. Carnahan	A. Cazes	S. Chen
P.L. Cole	P. Collins	P. Coltharp	P. Corvisiero
D. Crabb	H. Crannell	V. Crede	J.P. Cummings
R. De Masi	R. DeVita	E. De Sanctis	P.V. Degtyarenko
H. Denizli	L. Dennis	A. Deur	C. Djalali
J. Donnelly	D. Doughty	P. Dragovitsch	M. Dugger
S. Dytman	O.P. Dzyubak	H. Egiyan	P. Eugenio
R. Fatemi	G. Fedotov	R.J. Feuerbach	H. Funsten
M. Garcon	G. Gavalian	K.L. Giovanetti	F.X. Girod
J.T. Goetz	E. Golovatch	A. Gonenc	R.W. Gothe
K.A. Griffioen	M. Guidal	M. Guillo	N. Guler
L. Guo	V. Gyurjyan	C. Hadjidakis	K. Hafidi
R.S. Hakobyan	J. Hardie	D. Heddle	F.W. Hersman

K. Hicks	I. Hleiqawi	M. Holtrop	M. Huertas
C.E. Hyde-Wright	Y. Ilieva	D.G. Ireland	B.S. Ishkhanov
E.L. Isupov	H.S. Jo	K. Joo	H.G. Juengst
C. Keith	J.D. Kellie	M. Khandaker	K.Y. Kim
K. Kim	W. Kim	A. Klein	F.J. Klein
M. Klusman	M. Kossov	L.H. Kramer	V. Kubarovsky
J. Kuhn	S.V. Kuleshov	J. Lachniet	J.M. Laget
J. Langheinrich	D. Lawrence	Ji Li	A.C.S. Lima
K. Livingston	H. Lu	K. Lukashin	M. MacCormick
N. Markov	B. McKinnon	J.W.C. McNabb	C.A. Meyer
T. Mibe	K. Mikhailov	R. Minehart	M. Mirazita
R. Miskimen	V. Mokeev	L. Morand	S.A. Morrow
M. Moteabbed	G.S. Mutchler	P. Nadel-Turonski	J. Napolitano
R. Nasseripour	S. Niccolai	G. Niculescu	I. Niculescu
B.B. Niczyporuk	M.R. Niroula	R.A. Niyazov	M. Nozar
G.V. O'Rielly	M. Osipenko	A.I. Ostrovidov	K. Park
E. Pasyuk	C. Paterson	S.A. Philips	J. Pierce
N. Pivnyuk	D. Pocanic	O. Pogorelko	E. Polli
S. Pozdniakov	B.M. Preedom	J.W. Price	D. Protopopescu
L.M. Qin	B.A. Raue	G. Riccardi	G. Ricco
M. Ripani	F. Ronchetti	G. Rosner	P. Rossi
D. Rowntree	F. Sabatie	C. Salgado	J.P. Santoro
V. Sapunenko	R.A. Schumacher	V.S. Serov	Y.G. Sharabian
J. Shaw	N.V. Shvedunov	A.V. Skabelin	E.S. Smith
L.C. Smith	D.I. Sober	A. Stavinsky	S.S. Stepanyan
B.E. Stokes	P. Stoler	S. Strauch	R. Suleiman
M. Taiuti	S. Taylor	D.J. Tedeschi	U. Thoma
R. Thompson	A. Tkabladze	S. Tkachenko	L. Todor
C. Tur	M. Ungaro	A.V. Vlassov	D.P. Weygand
M. Williams	M.H. Wood	A. Yegneswaran	J. Yun
L. Zana	J. Zhang	B. Zhao	Z. Zhao

The members of the hypernuclear collaboration are listed below.

A. Margaryan	Yerevan Physics Institute, Armenia	L. Tang	Hampton University, USA
O. Hashimoto	Tohoku Univbersity, Japan	J. Reinhold	Florida International University, USA
Ed. Hungerford	University of Houston, USA	M. Furic	University of Zagreb, Croatia
F. Garibaldi	Istituto Nazionale di Fisica Nucleare, Italy	S.N. Nakamura	Tohoku Univbersity, Japan

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.

A.B., cum laude, Franklin and Marshall College, 1979.

Experience

2008-present - Clarence E. Denoon Professor of Science, University of Richmond.

2004-present - Professor of Physics, University of Richmond.

2002-2003 - Scientific Consultant, Jefferson Laboratory.

1999-2000 - American Association for the Advancement of Science Defense Policy Fellow.

1994-1995 - Scientific Consultant, Jefferson Laboratory.

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 Grants

1990-present - US Department of Energy ($1,361,000).

2002-2003 - SURA Sabbatical Support ($10,000).

2002-2003 - Jefferson Laboratory Sabbatical Support ($28,335).

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).

1994-1995 - CEBAF Sabbatical Support ($24,200)

1992-1995 - National Science Foundation ($49,813).

1989-1991 - Research Corporation($26,000).

1987-2007 - University of Richmond Research Grants($13,082).

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.

2002 - 2003 - American Physical Society Task Force on Countering Terrorism.

2000 - 2006 - Chair, Department of Physics.

2000 - Reviewer, US Department of Defense.

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

1. K.Sh. Egiyan, G.A. Asryan, N.B. Dashyan, N.G. Gevorgyan, J.-M. Laget, K. Griffioen, S. Kuhn, *et al.* (The CLAS Collaboration), 'Study of Exclusive d(e,e'p)n Reaction Mechanism at High Q2', Phys. Rev. Lett. **98**, 262502 (2007).

2. M. Battaglieri, R. De Vita, V. Kubarovsky, *et al.*, (The CLAS Collaboration), 'Search for $\theta^{+}(1540)$ pentaquark in high statistics measurement of $\gamma p \rightarrow \overline{K}_0 K^{+} n$ at CLAS', Physical Review Letters 96, 042001 (2006).

3. D. Protopopescu, *et al.*, (The CLAS Collaboration), 'Survey of A'_{LT} asymmetries in semi-exclusive electron scattering on ^{4}He and ^{12}C', Nuclear Physics, A748, 357 (2005).

4. K. Joo, *et al.*, (The CLAS Collaboration), 'Measurement of Polarized Structure Function σ'_{LT}) for $p(\vec{e}, e'p)\pi^0$ from single π^0 electroproduction in the Delta resonance region', Physical Review C, Rapid Communications, **68**, 032201 (2003).

5. B. Mecking, *et al.*, (The CLAS Collaboration), 'The CEBAF Large Acceptance Spectrometer', Nucl. Instr. and Meth., **503**/3, 513 (2003).

6. G.P.Gilfoyle and J.A.Parmentola, 'Using Nuclear Materials to Prevent Nuclear Proliferation', Science and Global Security **9**, 81 (2001).

7. G.P.Gilfoyle, 'A New Teaching Approach to Quantum Mechanical Tunneling', Comp. Phys. Comm., **121-122**, 573 (1999).

8. G.P.Gilfoyle, M.S.Gordon, R.L.McGrath, G.Auger, J.M.Alexander, D.G.Kovar, M.F. Vineyard, C.Beck, D.J. Henderson, P.A.DeYoung, D.Kortering, 'Heavy Residue Production in the 215 MeV ^{16}O+^{27}Al Reaction', Phys. Rev., **C46**, 265(1992).

Selected Presentations

1. "Measuring the Fifth Structure Function in $D(\vec{e}, e'p)n$", poster presented at the Gordon Conference on Photonuclear Reactions, Tilton, New Hampshire, August 10-15, 2008.

2. "Review of QCD Processes in Nuclear Matter at Jefferson Lab", presented at the XVI Workshop on Deep Inelastic Scattering and Related Subjects", London, England, April 8, 2008.

3. "A High-Precision Measurement of G_M^n with CLAS", Workshop on Exclusive Reactions at High Momentum Transfer, Newport News, VA, May 22, 2007.

4. 'Measurements of the Fifth Structure Function of the Deuteron', CLAS Collaboration Meeting, March 3, 2006.

5. 'Out-of-Plane Measurements of the Structure Functions of the Deuteron', plenary session of the CLAS Collaboration Meeting, November 13, 2003.

6. 'Maintenance and Upgrading of the Richmond Physics Supercomputing Cluster', V.Davda and G.P.Gilfoyle, Program and Abstracts for the Fall 2003 Meeting of the Division of Nuclear Physics of the American Physical Society, Tucson, AZ, Oct 30 - Nov 1, 2003.

7. 'Using Nuclear Materials to Prevent Nuclear Proliferation', colloquium presented at Thomas Jefferson National Accelerator Facility, Norfolk, VA, March 7, 2001.

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
2003-2006 - Professor G, Saha Institute Of Nuclear Physics
1996-2003 - Professor F, 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
1995 - Center Of Excellence Professor Award, Ministry of Education, Science, Sports and Culture (MONBUSHO), Japan
2003 - Affiliate Professor, Virginia Commonwealth University, Richmond, Va.

Refereed Publications

1. D.N. Basu, P. Roy Chowdhury and C. Samanta 'Nuclear equation of state at high baryonic density and compact star constraints', Nuclear Physics A811 (2008) 140.

2. C. Samanta, P. Roy Chowdhury and D. N. Basu 'Lambda hyperonic effect on the normal driplines', Jour. Phys. G **35** (2008) 065101.

3. P. Roy Chowdhury, C. Samanta and D. N. Basu, 'Search for long lived heaviest nuclei beyond the valley of stability', Phys. Rev. C **77**, 044603 (2008).

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)

5. C. Samanta , P. Roy Chowdhury, and D. N. Basu, 'Predictions of Alpha Decay Half lives of Heavy and Superheavy Elements', Nucl. Phys. A **789**, 142 (2007)

6. P. Roy Chowdhury, C. Samanta and D. N. Basu 'Alpha Decay chains from element 113', Phys. Rev. C **75**, 047306 (2007)

7. D. N. Basu, P. Roy Chowdhury, and C. Samanta 'Equation of state for isospin asymmetric nuclear matter using Lane potential' Acta Physica Polonia **37** (2006) 2869

8. S. Adhikari, C. Basu, C. Samanta, S. S. Brahmachari, B. P. Das, and P. Basu 'Performance of an axial gas ionization detector' IEEE Transactions on Nuclear Sciences, **53** (2006) 2270

9. C. Samanta, P. Roy Chowdhury and D. N. Basu 'Generalized mass formula for non-strange and hyper nuclei with SU(6) symmetry breaking', Jour. Phys. G: Nucl. Part. Phys.**32**, (2006) 363, nucl-th/0504085

10. P. Roy Chowdhury, C. Samanta and D. N. Basu, 'Alpha decay half-lives of new superheavy element', Phys. Rev. C **73** (2006) 014612, nucl-th/0507054

11. R. Kanungo, et al.,'Observation of a two-proton halo in Ne-17', Euro. Phys. Jour A **25** (2005) 327-330 Suppl. 1

12. D. N. Basu, P. Roy Chowdhury, and C. Samanta, 'Folding model analysis of proton radioactivity of spherical proton emitters ', Phys. Rev. C **72** (2005) 051601 (R),

13. P. Roy Chowdhury, C. Samanta, D. N. Basu ,'Modified Bethe-Weizscker mass formula with isotonic shift and new drip lines ' , Mod. Phys. Lett. **A21** (2005)1605

14. C. Samanta, 'Mass formula from normal to hypernuclei' (Invited Talk) Proceedings of the Carpathian Summer School of Physics 2005 (Exotic Nuclei and Nuclear/Particle Astrophysics), Mamaia-Constanta, Romania 13 - 24 June 2005 ed. by S. Stoica, L. Trache, and R. E. Tribble, World Scientific, Singapore, p. 29

15. C. Samanta,P. Roy Chowdhury andD. N. Basu (Invited Talk) 'Modified Bethe-Weizscker mass formula with isotonic shift, new driplines and hypernuclei', AIP Conference Proceedings **802**, 142 (2005)

16. S.Adhikari, C.Samanta, C.Basu, B.J.Roy, S.Ray, A.Srivastava, K.Ramachandran, V. Tripathi, K.Mahata, V.Jha, P.Sukla, S.Rathi, M.Biswas, P.Roychowdhury, A.Chatterjee, and S.Kailas, "Reaction mechanisms with loosely bound nuclei 7Li +6Li at forward angles in the incident energy region 14-20 MeV", Phys. Rev. C **74** (2006) 024602.

17. R. Kanungo, M. Chiba, N. Iwasa, S. Nishimura, A. Ozawa, C. Samanta, T. Suda, T. Suzuki, Y. Yamaguchi, T. Zheng and, I. Tanihata "Experimental evidence of core modification in near drip-line nucleus 23O", Phys. Rev. Lett. **88** (2002) 142502.

18. C.Samanta, N.S.Chant, P.G.Roos, A.Nadasen and A.A.Cowley, "^{16}O(α,αp) and ^{40}Ca(α,αp) reactions at 139.2 MeV incident energy ", Phys. Rev.C **35** (1987) 333.

19. C.Samanta, N.S.Chant, P.G.Roos, A.Nadasen, J.Wesick and A.A.Cowley, "Tests of the factorized distorted-wave impulse approximation for (p, 2p) reaction", Phys. Rev.C **34** (1986) 1610.

20. C.Samanta, N.S.Chant, P.G.Roos, A.Nadasen and A.A.Cowley, "Discrepancy between proton and alpha induced cluster knockout reactions on 16O", Phys. Rev C **26** (1982) 1379.

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.