Project Description

July 13, 2006

1 Results from Prior NSF Support

The Department of Physics at the University of Richmond (UR) received funding for an Instrumentation and Laboratory Improvement grant from the National Science Foundation for the proposal entitled "Video Technology in Introductory Physics" submitted in 1994. The award (grant # 9551066) was for $7,943 from NSF with matching funds from the University. The grant period started May 1, 1995 with a duration of twenty-four months.

In this project video technology was introduced into the introductory, workshop physics course for science majors to improve the students' learning of the fundamental ideas of Newtonian mechanics. With the use of low-cost video cameras the students record the trajectories of objects, digitize and store the data on a computer, and then analyze the observed motions frame-by-frame to 'discover' the features of the observed phenomena. This technique allows students to directly confront their preconceptions about motion, it measures the same quantities that are used to describe motion in the classroom such as the time-dependent position of a projectile, and it makes new and challenging phenomena accessible in the introductory physics laboratory. In addition, the method is flexible and easy to use, an essential, practical ingredient in an inquiry-based laboratory.

The project was implemented by developing new laboratory exercises that use video analysis techniques to study a broad range of phenomena including free-fall, projectile motion, uniform circular motion, conservation of energy, conservation of momentum, center-of-mass motion, collisions, rolling, conservation of angular momentum, and simple harmonic motion. Low-cost video cameras were purchased from Polaris Industries to record the movies. These are essentially video cameras on printed circuit boards and sturdy, metal housings were developed for these cameras at UR. The Macintosh computers in the introductory laboratory were upgraded as part of this project (the University has upgraded the computers since then) and video analysis cards were purchased to digitize and store the movies on the computers. The '2D Video QT' software developed at Dickinson

College [1] was used to analyze the videos during the first two years of the project. Since then, VideoPoint software has been used. Other equipment was also developed at UR for use in the video analysis exercises. For example, model airplanes were constructed from small, battery-operated motors, PVC pipes, and balsa wood for use in the uniform circular motion labs.

All of the goals of the project have been reached. Video analysis techniques have become an integral component of the inquiry-based, introductory physics course at UR. These techniques allow students to study the traditional introductory physics topics in a new and particularly enlightening way and enable the investigation of new phenomena. The student response to the video analysis methods and the workshop physics course in general have been very positive. Results on the Motion & Force Conceptual Evaluation [2], which is administered on the first and last classes of the first semester of the course, indicate that the course is quite successful in improving the students' conceptual understanding of Newtonian mechanics. The workshop physics course at UR has also attracted considerable attention from colleagues at other institutions with visits from several colleges and universities in Virginia and an invited talk at the Associated Colleges of the South Workshop on Computer-Based Physics Labs [3].

2 Research Activities

Funds are requested in this proposal to develop a computer cluster to support the UR research program in electromagnetic nuclear physics in Hall B at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The UR nuclear and particle physics research group consists of three faculty members (Gerard P. Gilfoyle, Philip D. Rubin, and Michael F. Vineyard) and typically 7-10 undergraduate students. The work is supported by the U.S. Department of Energy (Vineyard and Gilfoyle) and the National Science Foundation (Rubin).

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab provides a unique tool for basic research in nuclear physics. The central instrument of CEBAF is a superconducting electron accelerator with a maximum energy of 4-6 GeV, a 100% duty cycle, and a maximum current of 200 μA. These excellent beam characteristics allow for novel experiments that are being used to develop a quark-based fundamental understanding of nuclei.

The electron beam at CEBAF is used simultaneously for scattering experiments in three halls that contain complimentary experimental equipment. The primary instrument in Hall B is the CEBAF Large Acceptance Spectrometer (CLAS) [4, 5] shown in Figure 1. This device is a toroidal multi-gap magnetic spectrometer. The magnetic field is generated by six iron-free superconducting coils. The particle detection system consists of drift chambers [6] to determine the trajectories of charged particles, Cerenkov detectors [7] for the identification of electrons, scintillation counters for time-of-flight measurements [8], and electromagnetic calorimeters [9] to identify electrons and to detect photons and neutrons. The six segments are instrumented individually to form six independent spectrometers. The CLAS detector is capable of acquiring approximately 0.5 Terabytes of data per day. Hall B also houses a bremsstrahlung photon tagging system [10] that allows for experiments with real photon beams.

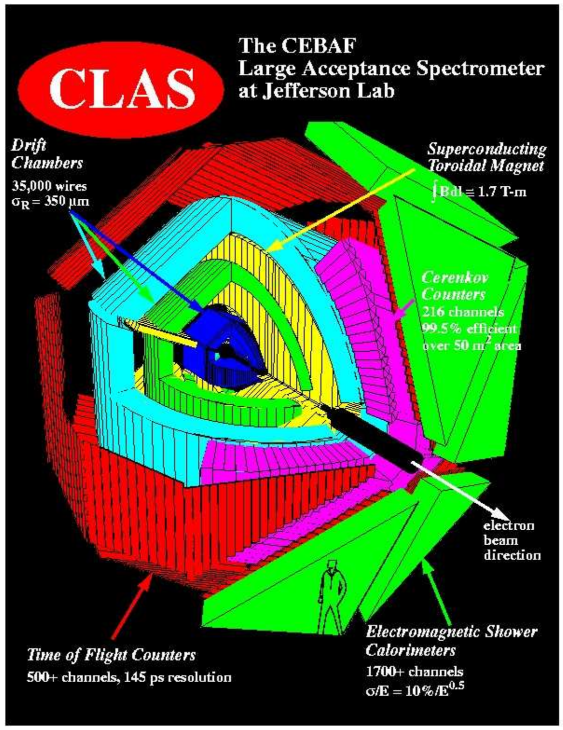

Figure 1: The CLAS detector.

The CLAS detector was constructed and is operated by an international collaboration consisting of thirty-five institutions. After nearly a decade of planning and construction, the CLAS Collaboration began production running in 1997 and the first physics results were published last year [11]. The UR group has been part of the CLAS Collaboration since its inception, and has been actively involved in the construction of the spectrometer and the development of the physics program.

The physics interests driving the group's efforts at Jefferson Lab are in the study of the structure, interactions, and nuclear-medium modifications of mesons and baryons. Three

CLAS experiments are listed in Table 1 and described in this proposal in which the UR group has particular interest. Experiment E-89-043 measures the electroproduction of the Λ, $\Lambda^*(1520)$ and $f_0(980)$ to determine production amplitudes and investigate the structure of the $f_0(980)$ scalar meson. Measurements of inclusive η photoproduction in nuclei are being performed in experiment E-93-008 to investigate nuclear medium modifications of the $S_{11}(1535)$ and $P_{11}(1710)$ nucleon resonances and the η-nucleon interaction. In experiment E-94-017 the magnetic form factor of the neutron will be determined from precise measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium. These experiments, which are described in more detail below, have all collected data in the last two years that will be analyzed during the funding period of this proposal.

Experiment	Title	Spokesperson(s)
E-89-043	Measurements of the Electroproduction of the Λ, $\Lambda^*(1520)$ and $f_0(980)$ via the $K^+\pi^-p$ and K^+K^-p Final States	L. Dennis, H. Funsten, G. P. Gilfoyle
E-93-008	Inclusive η Photoproduction in Nuclei	M. F. Vineyard
E-94-017	The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Electron-Neutron to Electron-Proton Scattering in Deuterium	W. Brooks, M. F. Vineyard

Table 1: List of CLAS experiments of primary interest to the University of Richmond research group.

The UR group's service to the CLAS Collaboration includes service as Experimental Coordinator (ECO) during several run periods, detector calibrations, data analysis, development and management of a prototype computing farm for simulations and analysis, and development and maintenance of software for controls, monitoring, data analysis, and simulations. Gilfoyle is responsible for the development and maintenance of an on-line version of the CLAS data reconstruction software, and has made many significant contributions to the analysis software for the drift chambers. Vineyard, who is on sabbatical leave at Jefferson Lab this year (August 2000 - May 2001), served as ECO for periods during the G2, G3, and E5 runs and is serving as analysis coordinator for E5. He is also managing the computer farm and is responsible for the development and maintenance of the controls software for the drift chamber and Cerenkov gas systems.

As always, undergraduate students are involved in all phases of these projects (UR is a primarily undergraduate institution). The involvement of students in research as part of their undergraduate education is an important part of the process of recruiting and training bright young people for careers in science. The Department of Physics at UR is dedicated to this process. Fourteen undergraduate students have participated in nuclear physics research at UR in the last three years. The funding of this proposal will help the group to continue to provide meaningful research experiences for many more undergraduate students.

2.1 Electroproduction of the $f_0(980)$, $\Lambda(gnd)$, and $\Lambda(1520)$

Considerable evidence now exists suggesting our current understanding of nuclei and nucleons is incomplete and the presence of strange quarks has a significant impact on nuclear dynamics. The experiment described here, like others proposed by the UR nuclear and particle physics group, will investigate the production of strangeness in reactions on the nucleon. It has been approved by the CEBAF PAC and began collecting data as part of the e1 running period. The analysis of these data will be one of the primary foci of the University of Richmond effort in the next few years.

The structure of the $f_0(980)$ scalar meson has been an ongoing controversy for the last twenty years. It was originally believed to be the $s\overline{s}$ inhabitant of the ${}^3P_0$ nonet and an $l = 1$ orbital excitation of the ω. However, there are inconsistencies between this assignment and the properties of other members of the nonet. The mass of the $f_0(980)$ is too small (by about 200 MeV) and its width is too narrow (by about a factor of 10). Its coupling to the K^+K^- decay channel is large at energies above the two-kaon threshold when calculations predict it should be less than the coupling to the $\pi^+\pi^-$ channel [12]. Note that the low-mass portion of the $f_0(980)$ resonance is below the energy needed to produce two kaons ($987MeV$). In addition, the nonet is now oversubscribed and there exist other candidates for the $s\overline{s}$ member [13]. Other experiments have found evidence for the existence of a scalar meson with the mass, width, and decay properties consistent with the other members of the nonet [14].

A variety of models have been proposed to account for the properties of the $f_0(980)$. These include $K\overline{K}$ molecules, 'cryptoexotic' $q^2\overline{q}^2$ states, scalar glueballs, hybrid mesons, and even a 'vacuum scalar' state [12, 15, 16, 17, 18]. The theoretical interest in the question of the nature of the $f_0(980)$ continues unabated [20, 21]. The experimental situation is also unclear. Results from the OPAL experiment at LEP are consistent with a conventional $q\overline{q}$ state [19]. Preliminary results from the Spherical Neutral Detector at the VEPP-2M e^+e^- collider have been interpreted as evidence for the $q^2\overline{q}^2$ MIT-bag model. This last result would imply little $s\overline{s}$ content in the $f_0(980)$ [22]. Nevertheless, results from the E687 experiment at Fermilab reveal a strong $f_0(980)$ signal in D_s decays that is not present in the decay of the non-strange D meson. This result contradicts the previous one and implies a significant hidden-strangeness component in the $f_0(980)$ [23]. The question is still open.

The existing data set cannot distinguish between these competing models. However, the excellent beam characteristics at Jefferson Lab and the large solid angle coverage of the CLAS hold the promise of resolving this controversy. The models predict different sizes and/or require different numbers of quarks in the $f_0(980)$ so the cross sections and W, t, and Q^2 dependencies will vary. Measurement of these dependencies will be through the primary decay modes of the $f_0(980)$, the K^+K^- and $\pi^+\pi^-$ channels. The $s\bar{s}$ content of the two-kaon decay mode makes it an ideal probe for the strange-quark effects in the $f_0(980)$. However, the two-kaon channel is not open until the energy exceeds the threshold at 987MeV. Above this energy threshold the two-kaon threshold K^+K^- dominates, so a strong signal can be expected. The $\pi^+\pi^-$ decay channel is the primary one at energies below the two-kaon threshold. While a variety of other background processes can contribute to the two-pion production, this channel does have advantages over the K^+K^- channel. It avoids the decays associated with the overlapping $a_0(980)$ (which decays via K^+K^- and not $\pi^+\pi^-$) and it is not distorted by threshold effects like the two-kaon channel. Other researchers have emphasized the need for both sets of data to unravel the properties of the $f_0(980)$ [24].

The amplitude for $f_0(980)$ decay is small, but it is near in mass to the $\rho(770)$ (for the $\pi^+\pi^-$ decay) and the $\phi(1020)$ (for the K^+K^- decay) which have large amplitudes. The overlap of the production amplitudes means they will interfere with one another and influence the decay angular distribution $W(\theta, \phi, \Phi)$ where θ and ϕ are the polar and azimuthal angles and Φ is the angle between the electron and hadron scattering planes. The interference term between the $f_0(980)$ and its neighboring $\rho(770)$ or $\phi(1020)$ will enhance the effect of the $f_0(980)$ amplitude. The $\rho(770)$ and the $\phi(1020)$ are diffractively produced so their helicity amplitudes are approximately known and this knowledge can be exploited to measure the $f_0(980)$ electroproduction amplitudes from the $W(\theta, \phi, \Phi)$ interference terms. Our simulations reveal that we can extract the amplitude of the $f_0(980)$ down to a level of about 10% of the amplitude of the neighboring meson. Once this amplitude is determined the cross section and W dependence of the sum of the phase angles for the two primary decay modes can be extracted. This last quantity in particular can be used to discriminate among the models [24].

Another way to study strangeness production on the nucleon is through reactions that involve the exchange of a kaon. The reaction $ep \rightarrow e'\Lambda K$ is an example. This reaction has been measured, but the results of the analysis are ambiguous. There are several possible candidates for the exchanged particle and one expects from spin effects that the exchanged particle in the case of the $\Lambda(1520)$ production should be the $K(892)$. However, fits to the measured data reveal the possible presence of a considerable contribution from other kaons [25]. To study the ΛK system we have measured the decay $\Lambda(gnd) \rightarrow p\pi^-$ and

$\Lambda(1520) \to K^- p$. Extracting the decay angular distribution will enable one to determine the predominant production diagram and the spin of the exchanged particle. For t-channel or s-channel processes the choice of analysis frame (e.g., helicity frame versus Gottfried-Jackson frame) is essential in determining the exchanged particle. The large solid angle coverage of the CLAS enables one to measure the full angular distribution of the decay products of the $\Lambda(1520)$ and to study the Q^2 dependence of the reaction. These data can then be used to identify the exchanged particle. Notice that a common feature of our investigation of these reactions is the need to measure the full angular distribution of the decay products of the $f_0(980)$, $\Lambda(gnd)$, and $\Lambda(1520)$, so the large-angle coverage of the CLAS is essential.

Experiment E89-043 has run as part of the E1 running period at CLAS which is largely complete and being analyzed. The analysis is being performed by groups from the University of Richmond and Florida State University. The analysis of the $\Lambda(1520)$ and $\Lambda(116)$ data is being done by the Florida State group (Dennis, Barrow, and McAleer) and much progress has been made. Their work has been the subject of an internal CLAS-Analysis-Note and several talks at conferences [26, 27, 28, 29]. The analysis of the $f_0(980)$ data has just begun and is the responsibility of the Richmond group (Gilfoyle). This work has been on hold for the last year while Gilfoyle was on leave from the University as a Defense Policy Fellow for the American Association for the Advancement of Science in Washington, DC.

2.2 E-93-008: Inclusive η Photoproduction in Nuclei

Jefferson Lab Experiment 93-008 uses the CEBAF Large Acceptance Spectrometer (CLAS) and the photon tagging system in Hall B to measure inclusive η photoproduction in nuclei [30]. The primary motivation of this experiment is to investigate nuclear medium modifications of nucleon resonances and the η-nucleon interaction. The experiment was approved by Program Advisory Committee 6 in the summer of 1993. According to the run plan developed by the CLAS collaboration to maximize the scientific output of Hall B by exploiting the capability of the CLAS to simultaneously obtain data for experiments with similar running conditions, this experiment is being performed during the G2 and G3 running periods.

Through the study of the excitation, propagation, and decay of nucleon resonances in the nuclear environment one ultimately expects to understand how the strong interaction is affected by baryon structure. Over the last twenty years, a wealth of information on the Δ(1232) and its dynamics within the nuclear medium has been obtained through pion studies. However, very little is known about medium properties of the higher energy excited states of the nucleon. This is primarily due to the fact that the dominance of the Δ and the overlapping of higher resonances prevents studying one specific state by π-production experiments. The η meson, on the other hand, couples only with isospin-1/2 N^* resonances since it is an isoscalar particle, and therefore provides an excellent way to isolate these resonances. In this experiment, inclusive measurements of the photoproduction of η mesons in nuclei are performed to investigate medium modifications of the $S_{11}(1535)$ and $P_{11}(1710)$ resonances which are the only nucleon resonances of mass less than 2 GeV with significant η decay branches.

These measurements will also provide information on the η-nucleon interaction. Due to the lack of η beams, very little is known about the interaction of η mesons with nucleons. In this experiment, final-state interactions of the η meson propagating through the nucleus will be used to investigate the ηN interaction. The study of η interactions with nucleons and nuclei can provide significant tests of our understanding of meson interactions which has been developed through pion studies. Also a comparative study of the response of η and η' mesons in the nuclear medium may provide insight into the mixing in these two mesons and the structure of the η'.

Data have been obtained recently at Mainz for the inclusive reaction on ^{12}C, ^{40}Ca, ^{93}Nb, and ^{nat}Pb nuclei for photon energies $\leq$790 MeV [31]. These data are of high quality, however, the energy range covered is from threshold to just below the peak of the $S_{11}(1535)$ resonance. From the analysis of these data, it was concluded that the total cross section scales as $A^{2/3}$ and a Glauber model analysis indicated an ηN cross section of about 30 mb. No evidence of a shift in mass or a depletion of strength of the $S_{11}(1535)$ was observed from a comparison with the effective Lagrangian model of Carrasco [32]. However, it should be stressed that this conclusion was drawn from a comparison of the slopes of the data and calculations on the low-energy side of the $S_{11}(1535)$ rather than over the entire line shape of the resonance.

There have been a number of recent theoretical results on η photoproduction from nuclei. In the effective Lagrangian approach of Carrasco *et al.* [32], the ηN final state interactions are taken into account by a Monte Carlo code using calculated reaction probabilities. In the work of Lee *et al.* [33], the quasifree production is calculated in the distorted-wave impulse approximation and the final state interactions are treated with an ηA optical potential. Effenberger *et al.* [34] use the production cross sections on the free nucleon as input and take into account the final state interactions with a coupled-channel Boltzmann-Uehling-Uhlenbeck model. All three models provide reasonable descriptions of the Mainz total cross sections. However, detailed agreement with the differential cross sections is not obtained with any of the models.

The Jefferson Lab experiment discussed here will extend the Mainz measurements to higher energies and more targets. The extended energy range will completely cover the region of the $S_{11}(1535)$ resonance and allow for a more thorough investigation of possible nuclear medium modifications. It will also allow for the measurement of contributions to the cross section from the $P_{11}(1710)$ resonance and non-resonant production. The measurements are being made on ^2H, ^3He, ^4He, and ^{12}C targets enabling the study of the evolution of medium effects with target mass and the investigation of the ηN interaction.

The G2 run period collected data for about 25 days in August and September of 1999. Nearly 2.5 billion photon-induced events from a liquid deuterium target were recorded. Data were taken at electron beam energies of 2.4 and 3.1 GeV corresponding to photon energy ranges of 0.6-2.3 GeV and 0.78-2.9 GeV, respectively. In addition to a single charged-particle trigger, a neutral trigger was used in the CLAS for the first time in this experiment. The neutral trigger consisted of hits in any two of the six forward-angle and two large-angle calorimeter modules. The detectors have been calibrated and the preliminary analysis of the data, or cooking as it is referred to in the Collaboration, has been completed. One of the UR undergraduate students developed a code that was used during the cooking process to filter out events with at least two neutral particles. The filtered data files are being moved from Jefferson Lab over the internet to the prototype computer cluster at UR where they are further analyzed to produce data summary files to be used in the physics analysis for E-93-008. Shown in Figure 2 is a preliminary invariant mass spectrum for $\gamma\gamma$ events recorded during the G2 run. The spectrum has been fitted with a function consisting of a quadratic piece to describe the background in the mass region 0-0.23 GeV, an exponential part to fit the background in the mass range 0.23-0.9 GeV, and two gaussians to fit the π^0 (mass $\cong$0.135 GeV) and η (mass $\cong$0.547 GeV) peaks.

The G3 run group received about 23 days of beam last December. Approximately 2 billion photon-induced events were recorded from liquid ^3He and ^4He targets. Data were taken at an electron beam energy of 1.6 GeV corresponding to the tagged photon energy range of 0.4-1.5 GeV. The calibration of the detectors for this run is currently being completed and the cooking of the data will begin soon.

2.3 E-94-017: The Neutron Magnetic Form Factor from Precision Measurements of the Ratio of Quasielastic Electron-Neutron to Electron-Proton Scattering in Deuterium

The CEBAF Program Advisory Committee Eight (PAC8) approved an experiment [35] (E94-017) to use CLAS to determine the neutron magnetic form factor from precise measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium over a squared four-momentum transfer, Q^2, range from 0.3 to 5.1 $(GeV/c)^2$. An extension [36] of this experiment was approved by PAC9 to make measurements with a 6-GeV beam and increase the Q^2 coverage to 7.5 $(GeV/c)^2$. The experiment began collecting data during the E5 running period of the CLAS Collaboration in April and May of

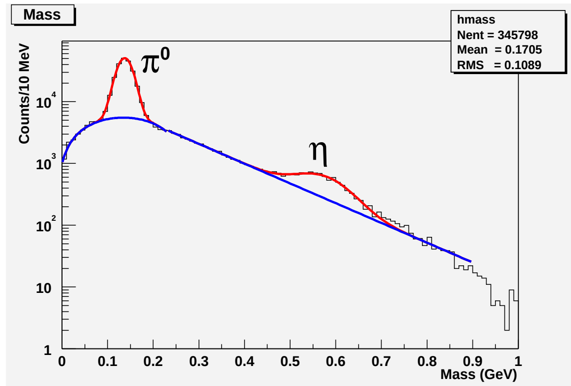

Figure 2: Invariant mass spectrum for $\gamma\gamma$ events recorded during the G2 run period of the CLAS Collaboration. The spectrum is fitted with a background function and two gaussian functions. The background function has a quadratic form over the range 0-0.23 GeV and an exponential form over the range 0.23-0.9 GeV. The π^0 (mass = 0.135 GeV) and η (mass = 0.547 GeV) peaks are fitted above the background with the gaussian functions.

2000.

Nucleon structure is one of the most fundamental issues in nuclear physics. Elastic electron scattering provides detailed information about the electromagnetic structure of the nucleon. The differential cross section for elastic electron-nucleon scattering in the one-photon-exchange approximation is given by the Rosenbluth formula [37] in which the nucleon structure information is contained in the Sachs electric and magnetic form factors. These form factors are used for comparison between experiment and theoretical models of nucleon structure. In addition to being of fundamental importance in understanding nucleon structure, the form factors are a necessary input for calculations of nuclear response functions.

The proton electromagnetic form factors have been rather well determined at low Q^2 values using a Rosenbluth separation [38], and more recently at higher Q^2 using a polarization transfer technique [39]. However, the neutron form factors have been determined with much less precision than those of the proton [38]. The reason for the large uncertainties in the neutron measurements is that most of these data come from analyses of inclusive quasielastic electron scattering from deuterium that introduce a number of significant systematic errors. Progress has been made in measurements [40] of the neutron magnetic form factor, G_M^n, at low Q^2 values by measuring the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium, a method in which many of the systematic uncertainties cancel. Although, there are discrepancies between these measurements. Recently, measurements [44] of inclusive quasielastic scattering of polarized electrons off a polarized ^3He target were performed in Hall A at Jefferson Lab that will yield another accurate measurement of G_M^n at low Q^2.

In this experiment, precise measurements of the ratio of quasielastic electron-neutron to electron-proton scattering in deuterium will be made over a Q^2 range from 0.3 to $7.5(GeV/c)^2$ with the CLAS. The neutron magnetic form factor will be extracted from this ratio with the use of the more accurately known proton form factors. Data are taken simultaneously on separated hydrogen and deuterium targets. The $e+p \rightarrow e'+n+\pi^+$ reaction on the hydrogen target will be used to measure the neutron detection efficiency. The data from electron-proton and electron-neutron scattering in deuterium will be treated in an identical way insofar as possible. The use of this ratio technique, with the simultaneous calibration of the neutron detection efficiency, significantly reduces or eliminates many of the systematic errors associated with quasielastic scattering from deuterium. The results of this experiment will provide a significant improvement in our knowledge of the neutron magnetic form factor over the Q^2 coverage of existing measurements, and will nearly double the range. In addition to providing accurate information on the magnetic structure of the neutron, these data will be important for the extraction of the electric form factor of the neutron from measurements of polarization observables which determine a linear combination of the electric and magnetic form factors (see for example Refs. [45, 46]).

The measurements at high momentum transfer will have special significance in relationship to QCD. It has been observed that the proton magnetic form factor falls off with Q^{-4} behavior beginning at about 5-10 $(GeV/c)^2$. A functional dependence of this type is predicted by quark dimensional scaling, but this level of interaction was expected to occur only at much higher momentum transfer. On the other hand, estimates of nonperturbative soft contributions indicate that the soft terms are comparable to the data in magnitude [47]. This has fueled a great deal of controversy over the validity of perturbative QCD at such low momentum transfer. This experiment will address this issue by providing the first reliable measurements of the neutron magnetic form factor in the momentum transfer range where the proton magnetic form factor exhibits the Q^{-4} behavior.

Data for E94-017 were collected during the E5 run in April and May of 2000 with the CLAS detector in Hall B at Jefferson Lab and are currently being analyzed. Approximately 2.3 billion triggers were acquired, about half at an electron beam energy of 2.6 GeV and half at 4.2 GeV. The low beam energy data was divided into two-thirds normal torus polarity and one-third reversed torus polarity. The reversed torus polarity data was taken to reach the lowest possible limit in Q^2. This data will provide the magnetic form factor of the neutron over the Q^2 range from 0.2 to 4.8 $(GeV/c)^2$, with uncertainties of a few percent over most of the range and many systematic cross-checks. These measurement should eclipse and extend the entire world's data for this fundamental quantity.

3 Description of Research Instrumentation Needs

We request in this proposal funds for the purchase of a cluster of twenty, dual-CPU, computers supported by 2.5 terabyte of disk storage and associated hardware and software to increase the productivity of our research efforts at the University of Richmond and at Jefferson Lab and to train our undergraduates in modern analysis methods. In this section we briefly discuss the physics projects motivating this request, how the proposed system will be used, and who will use it. We describe the current resources available to our group, our computational needs and present a detailed rationale for the proposed system.

The members of the University of Richmond Nuclear and Particle Physics group are spokespersons on a variety of approved experiments in Hall B at Jefferson Lab. The majority of the projects explore the influence of strange quarks on nuclear and nucleon dynamics and another one investigates the poorly-understood, magnetic structure of the neutron. Table 1 in Section 1 of this proposal lists these projects. All of the experiments listed in Table 1 will need a precise simulation of the acceptance to produce publication-quality measurements of cross sections, branching ratios, *etc.*. As we will show below, these tasks are CPU intensive and demand considerable computing power. The projects listed in Table 1 will also accumulate large quantities of data. Some of the analysis will be done at Jefferson Lab, but a large university-based effort is needed to complete the work. The volume of data is large and demands a large investment in computer disk space. The goal of this proposal is to acquire (1) adequate CPU power to simulate the CLAS acceptances and (2) sufficient storage space to efficiently perform 'second-pass' analysis of the CLAS data.

To satisfy these physics needs we propose developing an on-campus 'supercomputer' or cluster with 20 dual-Pentium computers operating in parallel. The proposed system builds on an existing cluster that we developed as a pilot project. A single node of the cluster will act as a firewall to restrict access to the system and reduce network traffic among the nodes of the cluster. Users will log into the system and use the Distributed Queuing System (DQS) to submit batch jobs. For Monte Carlo simulations using the CLAS simulation package GSIM, the Distributed Queuing System will select the least-used node and start the process on that CPU until all the desired machines are running. The simulated events will be reconstructed with the CLAS standard analysis package RECSIS. This reconstruction package is also used to analyze the CLAS data. Second-pass analysis will be performed on the data that is initially 'cooked' at Jefferson Lab and then downloaded from the CLAS tape silo over the internet. This work will also be done in batch mode with RECSIS and Physics Analysis Workstation (PAW) from CERN. Activities like editing files, compiling and linking modified versions of GSIM and RECSIS, and interactive data analysis or simulation will be restricted if not excluded from the cluster to increase speed.

The proposed instrument will be used by the faculty and students in the University of Richmond Nuclear and Particle Physics Group. Undergraduates will be intimately involved in the use of the proposed system. The University of Richmond's primary mission is undergraduate education (there are no graduate students in the Physics Department) and the University is committed to research involving undergraduates as a means to broaden our students education beyond the scope of the classroom. In the last decade we have routinely had 7-10 students each summer involved in nuclear and particle physics at Jefferson Lab and other national laboratories like Argonne and Brookhaven. The proposed instrument will make their research (and the faculty's) more productive and will train them on the most modern physics instruments. The cluster will also support other in in the CLAS collaboration. The GSIM Focus Group at Jefferson Lab is coordinating the effort to produce publication-quality acceptance calculations for the CLAS. One of us (Vineyard) is already working in this group and another (Gilfoyle) will start next summer. The group reviews and accepts proposals from the collaboration for long Monte Carlo simulation runs and then distributes the tasks to available computing clusters at Jefferson Laboratory, Old Dominion University, University of Virginia, and others. The system proposed here will join the clusters at those institutions. This use of the cluster by others in the collaboration will become one of the major components of our group's service contribution to the CLAS collaboration. It will be used to satisfy the computational demands of the University of Richmond Nuclear and Particle Physics Group and contribute to the computational resources of the CLAS collaboration.

The current computer system in the Nuclear and Particle Physics Group includes a computing cluster developed as a pilot project for this proposal plus an array of computers for software development and non-CPU-intensive calculations and analysis. The existing cluster was purchased with funds from our existing DOE grant and University funds in the summer of 1999. The system consists of twelve, dual-CPU, 500-MHz Pentium processors running the Linux operating system. Each machine has 36 GByte of disk space and 256 MByte of memory. In 2000, we added a network disk appliance with 480 MByte of usable space. The entire system resides on its own subnet and one of the twelve machines has an additional network card to handle all incoming network traffic and act as a firewall. We have learned two lessons based on our experience with this system. First, to efficiently perform the second-pass analysis that needs to be done on the CLAS data we require more disk space; enough to store all the cooked data from a single run period. Second, the CPU power of this cluster is not adequate to produce the needed simulations of the CLAS response in a timely manner. A typical acceptance calculation (of which there will be many) can take up to 40 days on our existing cluster. This is simply too long to expect the analysis to be complete in a reasonable amount of time. We present more details to support these conclusions below.

The remainder of the computer system consists of two Sun computers (an Ultra 1 and Ultra 60) supported by 17 GByte of disk storage and two CD-ROM readers. There are five PC's running Linux that are supported by another 24 GByte of disk space, a writable CD, an eight millimeter tape drive, and several printers and other peripherals. Six X-terminals provide access to these machines including the cluster.

The physics projects described in this proposal all have considerable computing demands. These demands involve the simulation of the CLAS detector to generate publication-quality acceptance functions and adequate disk space and CPU power to perform 'second-pass' analysis of the data. To estimate the CPU demands for simulating the CLAS consider the recent experience with the analysis of experiment E89-043. One of the goals of this CLAS experiment is to investigate the electroproduction of the $\Lambda(1520)$ hyperon. The analysis of this data is far along and the simulation of the response of the CLAS relevant to this reaction channel is complete. That simulation (which is similar to the one needed to study $f_0(980)$ electroproduction) required 40 million Monte Carlo events for each beam energy and each setting of the toroidal magnet of the CLAS. For the $\Lambda(1520)$ analysis there were four different electron beam energies used with two torus setting for each energy. These simulations were run over a period of many months on machines at Jefferson Lab and at Florida State University. Consider the time necessary to simulate the same number of events $N_{evt} = 40 \times 10^6$ and analyze them on our existing cluster. The typical event simulation rate in the package GSIM is $R_{gsim} \approx 1\ Hz$ on a 500 MHz computer when no secondary particles are simulated in inert volumes. Using the standard analysis code RECSIS to analyze each event fully gives an analysis rate $R_{recsis} \approx 1\ Hz$ on a similar machine. Our existing cluster has $N_0 = 24$ CPUs in it. The time T_0 to produce and analyze these simulated events is then

$$T_{now} = \frac{N_{evt}}{N_0 R_{gsim}} + \frac{N_{evt}}{N_0 R_{recsis}} = 3.3 \times 10^6\ s \approx 39\ days \qquad .$$

The simulation of the CLAS response for the analysis of the $f_0(980)$ could require almost six weeks on our existing cluster. Remember this calculation is for a single setting of the CLAS toroidal magnet and for a single beam energy. The data sets we will analyze typically have several combinations of magnet setting and energies. This calculation also ignores several competing activities. Other members of the group will be simultaneously performing simulations relevant to their studies. Second-pass analysis of the data will be performed on the same machines at the same time. Finally, some CPU time will be used for development, testing, and data transfer. These other activities will likely increase the time needed to perform the simulation by factors of several (2-5). The Jefferson Lab facilities are inadequate for all the computing demands of the CLAS collaboration and our existing cluster falls short of our needs. To close this gap additional computing power is necessary. The cluster proposed here will reduce the demand on the Jefferson Lab cluster, speed the calculation of the CLAS acceptance, and complete the analysis of the CLAS data.

The disk space demands for analysis of CLAS data are large. Table 2 below shows the volume of the data summary tapes for the three experiments discussed in this proposal. The existing data summary tapes sum to about 2.2 TBytes, but do not the include the

Experiment	Run Period(s)	Size of Raw Data (Terabytes)	Size of Data Summary Files (Terabytes)
E-89-043	E1B	1.0	0.8
E-89-043	E1C	17	0.9-1.8 (expected)
E-93-008	G2 + G3	12	0.90
E-94-017	E5	10	0.5

Table 2: Size of the CLAS experiment data sets.

files the E1C running period which have not yet been produced. Our existing cluster has 0.4 TBytes distributed across the twelve, dual-processor machines plus another 0.5 TBytes in a network disk appliance for a total of about 0.9 TBytes. To perform second-pass analysis in a timely fashion, we must be able to analyze the full data sets without repeatedly moving data on and off the system. This task requires enough disk space to hold all of the data summary tapes. Given the competition for computing resources on the Jefferson Lab computer cluster and the lack of sufficient disk space on our existing cluster this analysis would be more efficiently done on the proposed system. The disk space requested for the system in this proposal will enable us to store a large fraction of the data on disk where it can be analyzed in a timely fashion.

We now describe the proposed system that will satisfy our computational needs. The components are listed in Table 3. A detailed quote for items 1-14 is in the Appendix from VA Research. Below we discuss our reasoning behind the choice of the different pieces.

The dual-Pentium processors (item 1) were chosen because of their excellent cost-to-benefit ratio. The Linux operating system is a research-quality operating system that is becoming commonplace at Jefferson Lab and within the CLAS collaboration. We chose machines with Linux pre-installed to save time and to insure that all the hardware is compatible with the operating system. The number of machines was chosen to reduce the time to for simulating the CLAS response to a reasonable value. The proposed cluster with its existing machines plus the additional twenty nodes (with 40 CPUs) proposed here will generate and analyze 40 million events in a much shorter time; we estimate about 11 days. Consider the following calculation. The rate for simulating events will increase by about 50% since the machines will have speeds of about 750 MHz so $R'_{gsim} \approx 1.5\ Hz$. The

Item	Number	Description	Price($)
1	20	Dual Pentium II 1-GHz workstation pre-installed with Linux.	30,400
2	40	Quantum 18.2 GByte SCSI disk	24,000
3	20	Memory upgrade to 256 MByte	2,500
4	3	Network disk appliance (2.5 TByte total)	lots
4	21	Fast Ethernet card	979
5	1	24-port router	2,500
6	3	20-inch monitor	3,597
7	2	Monitor switch	700
8	2	HP 5648 DDS-3 tape drive	5,350
9	4	Backup power supply	502
10	21	Extended warranty	3,000
11	-	Hardware items that cost less than $500.	1,797
12	1	Shipping	608
13	10	Distributed Queuing System (DQS)	free
14	1	Software installation and training	1500
15	4	Racks to mount the system	431
		Total Cost	75,589

Table 3: Proposed computer cluster description and cost (see quotes in Appendix for more details).

same increase can be expected for reconstructing the events so $R'_{recsis} \approx 1.5\ Hz$. If we add $N_1 = 40$ CPUs to our existing cluster then the time T_1 to simulate $N_{evt} = 40 \times 10^6$ events is

$$T_1 = \frac{N_{evt}}{N_0 R_{gsim} + N_1 R'_{gsim}} + \frac{N_{evt}}{N_0 R_{recsis} + N_1 R'_{recsis}} = 9.5 \times 10^5\ s \approx 11\ days \qquad .$$

This is to be compared with the previous result of 40 days using only the existing cluster. The proposed machines reduce the time for an acceptance calculation by a factor of almost four.

It is worth discussing here some considerations for transferring data files from Jefferson Lab to the cluster. The University of Richmond expanded its internet capacity in January, 1999 to T3 speeds (45 million bits/s or Mbps). Using the software and guidance provided by the JLab Computing Center, we can transfer a 1-GByte file from the JLab computers to our cluster in about 16 minutes in the early evening (about 7 pm). This bandwidth is adequate for our needs.

Two disks (item 2) will be attached to each machine to provide 36 MByte of storage.

This space is needed to store the output of the GSIM simulations which will be analyzed by the RECSIS reconstruction code. The memory upgrade (item 3) will increase the speed of the cluster for large executables. The analysis and simulation packages (RECSIS and GSIM) use large amounts of memory so the upgrade is needed to reduce data swapping between memory and disk space. Fast ethernet cards (item 4) and the fast ethernet switch (item 5) are needed to speed data transfer over the network. One machine on our existing cluster will act as a firewall for the rest of the system. The remaining machines in the cluster will be relieved of responding to outside network traffic and access (and security) can be controlled and monitored through a single computer. One monitor (item 6) will be placed on the machine that is serving as a firewall. The monitor switch (item 7) will enable the system manager to communicate with all the machines from a single monitor quickly and easily. Two tape drives (item 8) will be used for backups. Backup power supplies (item 9) will prevent damage to the system in the event of a sudden power loss and the extended warranty (item 10) will insure that any items that fail are covered for the next three years. A variety of other components (item 11) each cost less than $500 (cables and video cards) and the shipping cost is listed in item 12. See the quote in the Appendix from VA Research for more details. The Distributed Queuing System (DQS) is a software package (item 13) that will will be used to submit batch jobs and manage the resources of the cluster. It was developed at the Supercomputer Research Institute at Florida State University by members of the CLAS collaboration and is now being used at Jefferson Lab. Software installation and training for the members of our research group (item 14) is needed to use DQS and some racks is needed to hold the system (item 15).

4 Impact of Infrastructure Projects

5 Project Management Plans

The system will be properly maintained. The expertise exists in the University of Richmond Nuclear and Particle Physics Group to develop and maintain the proposed computer cluster. Two of us (Rubin and Gilfoyle) are responsible for maintaining the existing systems and in the last year we have all gained experience with the Linux operating system. All members of our group have considerable software experience in general and with the codes used by CLAS and RadPhi. See the accompanying progress report for more details. The University has adequately supported our research efforts in the past and we expect them to continue supporting the University's technology infrastructure. The current upgrade of the internet connection to T3 speeds was, in part, in response to the needs of our group. The University also purchased three Linux workstations during the past year as part of their routine upgrade plan. The extended warranty will cover unforeseen equipment failures. Finally, we have modeled many features of the proposed computer cluster after existing ones at Jefferson Lab or within the CLAS collaboration. There is a significant amount of expertise within the collaboration that we can call on.

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