Sabbatical Proposal

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1 Statement of Purpose and Outline

1.1 Introduction

This document is a research proposal for a full-year sabbatical at the University of Richmond. The research proposed here builds on the successful program I have developed in electro-nuclear physics at the Thomas Jefferson National Accelerator Facility (Jefferson Lab or JLab) in Newport News, VA. That program is externally supported by the US Department of Energy and has involved many University of Richmond undergraduates in frontier research at a world-class facility. The primary scientific instruments at Jefferson Lab are a large, one-mile-around, electron accelerator and four large particle detectors or end stations which capture and measure the debris from collisions of the electron beam with nuclear targets. The laboratory is nearing completion of the 12 GeV Upgrade, a $300 million project that will open exciting new opportunities for fundamental research into the nature of matter. The projects discussed below include an investigation into the internal structure of the neutron, one of the primary constituents of all known matter, and the development of software for the reconstruction and analysis of data from CLAS12, one of the new end stations being built as part of the 12 GeV Upgrade. The completion of the 12 GeV Upgrade is the highest priority of the long-range plan for nuclear physics in the United States [1].

The main focus of the research is two-fold. (1) The magnetic form factor of the neutron is a fundamental quantity related to the distribution of electric charges and electric currents within the atomic nucleus. I am the spokesperson and leader of an approved experiment at JLab to measure the neutron form factor. This approval means that some time after the completion of the 12 GeV Upgrade about 60 days of beam time will be scheduled to make this measurement. In preparation for that experiment and as part of the effort to build the new particle detectors at Jefferson lab, I will be developing simulations of neutron collisions that are necessary for the design and construction of the detectors and for the planning future experiments. (2) I am a member of a large collaboration building CLAS12 (the particle detector that will occupy an end station at JLab). It is a wide acceptance device meaning it will detect most of the debris from collisions of the electron beam with nuclear targets and record the results electronically. We will collect about 10,000 gigabytes of data each day. Needless to say, the computing demands here are imposing. I am part of the group within the collaboration responsible for developing the software to reconstruct, analyze, and simulate these data. I will be writing code (with my students) that will used to analyze both the neutron form factor data and the results of other experiments.

I am planning on spending the full academic year on sabbatical (2015-2016) and I am pursuing funding from the US Department of Energy, Jefferson Science Associates, and other sources. I also plan to apply for an enhanced sabbatical from the University. In the remainder of this proposal I develop the physics background that motivates the proposed work and go into greater detail about the projects.

1.2 The Quest for Quarks

Nobody has ever seen a quark. Yet, physicists have no doubt about their existence and the central role they play at the very heart of all the matter in the world around us. Figure 1 shows the current, over-simplified, picture of the structure of matter. Within the atomic nucleus lie protons and neutrons (collectively called nucleons) that are in turn composed of three smaller particles; the quarks. Other particles, the gluons, pop in and out of existence in a bubbling soup inside the nucleus and, strangely enough, create the force that holds the quarks together. It is this force that poses one of the great challenges to our understanding of the Universe. Every other fundamental force we observe gets weaker as two particles get farther apart. This feature is what allows us to launch spacecraft to other planets and to generate electricity. The force that binds quarks together is different. It is constant regardless of the distance between the quarks. Pull two quarks a centimeter apart and the force is the same as when they are 10,000,000,000,000 times closer. This 'confinement' means we will never 'see' a bare quark.

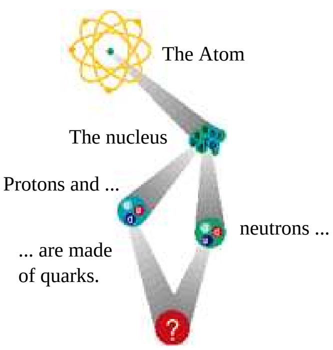

Fig 1. The structure of matter.

This is not the whole story. The best theory of the quark-quark force we have now is called quantum chromo-dynamics (QCD). QCD is built on observations made at very high energy where the environment is simpler and easier to understand, but where the conditions are different from the ones inside the nucleus. One of the main reasons for upgrading JLab is to understand the nature of confinement and how quarks combine to form protons and neutrons (the basic constituents of the matter we see all around us). We need to map out the features of the quarks as they go about their everyday lives inside the nucleus. A vital step in this nuclear cartography is to know where the electric currents located within the nucleus and its constituents.

In this Proposal I will describe two projects, but first let me describe how one takes data at JLab to set the stage for the description of the research projects. The JLab accelerator produces a electron beam by pushing the electrons through the mile-long, racetrack-shaped, machine up to five times (see Figure 2). This beam is extracted and sent into one of four experimental halls. It is in the halls where the action takes place. The electron beam strikes a nuclear target and a spray of debris is produced that we detect and measure. The detector I use is called the CEBAF Large Acceptance Spectrometer or CLAS12 (the '12' represents the 12 GeV Upgrade, CEBAF stands for the Continuous Electron Beam Accelerator Facility, the actual electron accelerator). This is a large (about 45 tons), \$50-million device that was built by my colleagues and me in the CLAS Collaboration. See Figure 3. The CLAS Collaboration consists of about 300 physicists from all over the world who are responsible for building, maintaining, and operating CLAS. The collision or event that I just described occurs about 10,000 times each second and we record about 10 terabytes (1 terabyte = 1000 gigabytes) of data per day.

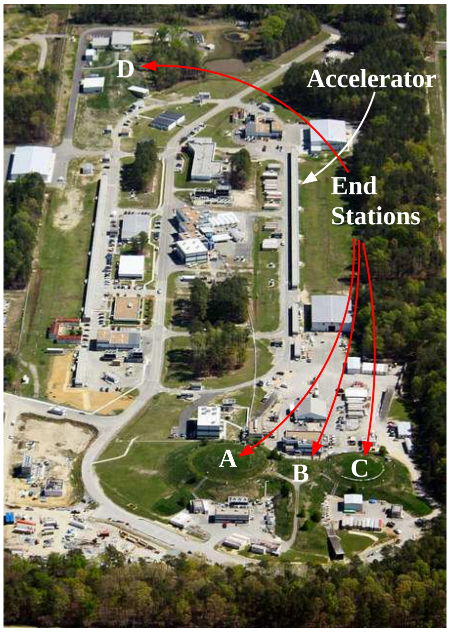

Fig 2. Jefferson Lab site.

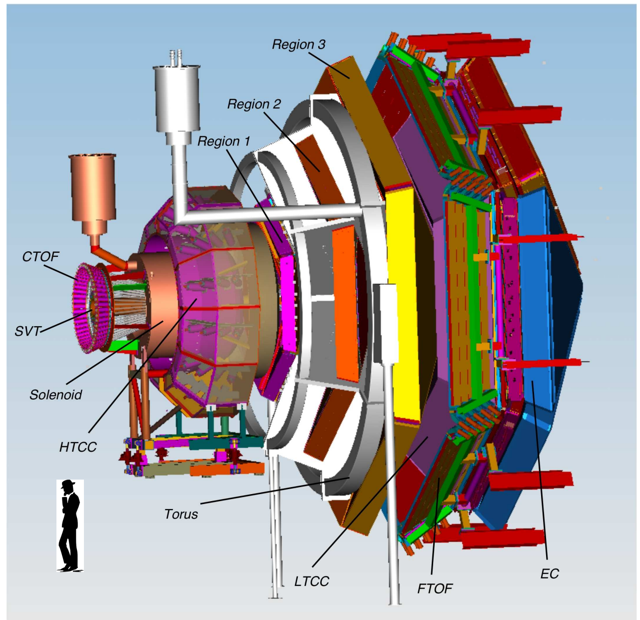

Fig 3. The CLAS12 detector.

1.3 The Magnetic Form Factor of the Neutron

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

The impact of this experiment will be large. We have used predictions of the neutron form factor to predict the range and quality of the data we will detect with CLAS12. Our expected results are shown in Figure 4. It shows a commonly used form of G_M^n plotted versus the quantity Q^2 which represents the size of the kick we impart to the neutron in the

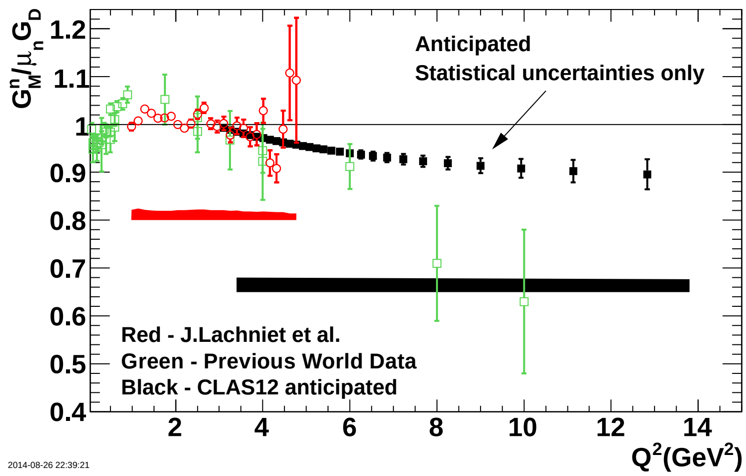

Fig 4. Our anticipated results for G_M^n with a selection of the world's data.

collision with the electron beam. The black points are our prediction and it represents the range and precision we expect to achieve. An earlier, similar measurement done by my collaboration (and me) is shown by the red points and the green points are a sample of the best measurements made from laboratories around the world [2].

The research plan for the measurement of G_M^n will now be described. We are in the planning and preparation stages for the experiment. The data will be collected for the nuclear reaction $e^2\mathrm{H} \rightarrow e'pn$ where the incident electron (e) strikes a deuterium (^{2}H) target. The debris from the collision consists of the scattered electron (e'), a proton (p), and a neutron (n). The measurement will be done with CLAS12. The preparations for this experiment include sophisticated, physics-based simulations of CLAS12 to understand its response so we can separate our physics results from backgrounds and artifacts of the detector. For example, I will use a simulation of the G_M^n target to better understand background particles that could contaminate our data. The development and analysis of these simulations will be the central focus of this part of my sabbatical.

1.4 Software for the CLAS12 Detector

To take full advantage of the new physics opportunities the CLAS12 detector is under construction to meet the requirements for the study of the structure of nucleons and nuclei after the 12 GeV Upgrade. Figure 3 shows a conceptual design of the new device. The height of the detector in the figure is about 10 meters.

I am committed to software 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 [3, 4, 5, 6]. I have been a member of the CLAS12 Software Group since its inception. The CLAS12 detector will have prodigious software requirements. The online data rate is expected to be 10 kHz with a 10 kByte event size and less than 15% deadtime [7]. We will collect about 8 petabyte (1 petabyte = 1,000,000 gigabytes) of data each year. Keeping pace with this deluge of data requires large computing facilities at JLab and at the universities in our collaboration. We expect to build a computing farm at JLab consisting of, essentially, 12,000 computers running in parallel [8]. It is worth noting the University of Richmond Physics computing cluster (obtained with a grant from the National Science Foundation, E. Bunn and G.P. Gilfoyle, principle investigators) has been an essential test bench for the new programs being written to support the CLAS12 physics program.

Calibration (understanding the response of CLAS12) and event simulation are essential aspects of operating CLAS12 and reaching the design goals for the detector. For many experiments, the quality of the results will be limited by systematic uncertainties instead of statistical ones. Accurate, precise calibrations and simulations of the CLAS12 response are important to keep those systematic uncertainties small. To do that we expect to generate about four times as much simulated, Monte Carlo data as CLAS12 collects. The CLAS12 simulation will produce data more slowly than the detector itself so the contribution of university groups to this effort is essential. The same issues that arise in designing the physics experiments also arise in the design and prototyping phase of the software project we are in now.

In particular, I will study of ways to calibrate/measure the alignment of the CLAS12 subsystems using cosmic rays. In other words, are the CLAS12 components (wires, light-emitting plastic scintillators, high-purity silicon) in the right place and, if not, how far off are they? An accurate knowledge of the CLAS12 geometry is necessary to reach the expected precision of the detector. CLAS12 is three stories high and we have to know the three-dimensional position of some of the components to within about a quarter of a millimeter - the size of the period at the end of this sentence. Cosmic rays are high energy particles that constantly bath the Earth. They can provide straight tracks through the CLAS12 subsystems and give us a tool to check the positions of the sub-system components. Turning on the CLAS12 magnetic field will bend the cosmic rays and would provide an additional way to check both the geometry and the reconstruction software. This project will use real cosmic ray data in the CLAS12 sub-systems and I will also develop a simulation of the cosmic rays for use with the CLAS12, physics-based simulation. A comparison can then be made between measured results and the simulated ones. These tests will be especially important for the central tracker in CLAS12 because it is small and located close to the target so misalignments can have significant impacts on the precision of the track reconstruction. I will be working on this project with Dr. Veronique Ziegler who is a staff member at JLab and head of the CLAS12 Software Group.

First beams are only two years away and Jefferson Lab is committed to the goal of being able to collect, calibrate, reconstruct, and analyze the data stream from day one. The work described here will be the subject of JLab reports and refereed instrumentation publications.

References

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2 Relationship to Teaching, Research, Department Aims, and University Needs

These sabbatical projects can enhance my teaching in two ways. I will gain a deeper understanding of the challenges and unknowns that lie at the frontier of physics. Even in my introductory physics courses I include much-simplified applications of physics principles to nuclear physics. Quarks moving through a large nucleus feel a analogous to the force of gravity acting on the objects around us. I will also be working at the technological frontier. Sophisticated computing is essential for the success of the 12 GeV Upgrade and that will inform the application of similar technologies in the classroom. In a previous sabbatical (many years ago) I learned how to use small video cameras attached to computers. After returning to the University I received funding from the National Science Foundation to incorporate that technology into our introductory physics courses at Richmond. The use of those cameras in our Department is now commonplace.

The program will continue and amplify my research productivity. I will focus exclusively on the work described here, playing my role in completing the 12 GeV Upgrade and preparing for the experiment to measure the neutron form factor. This will lead to publications, technical reports, and talks at conferences. This enhanced productivity will help me maintain my external funding that supports my students and me.

This sabbatical program will keep the intellectual life in the Physics Department at a high level. We have a very research active department (all the senior faculty are externally funded) and what I learn and do on sabbatical fits nicely with the ethos of the Department. Of course, maintaining my own external funding adds to the opportunities available for our students in Physics.

Last, the program builds the reputation of the University in the sciences. I am one of very few faculty from an undergraduate institution in our collaboration and funded by the US Department of Energy. My work places Richmond among institutions like MIT, UVa, Carnegie-Mellon, and others.

3 Location

Jefferson Lab is located in Newport News, VA. I will live in Newport News during the week so I can take full advantage of the facilities and my collaborators. There will be some travel to conferences and meetings with collaborators.

4 Other employment

I have no plans to do other, paid work during the period of the sabbatical.