

*Department of Energy*  
*Office of Nuclear Physics*

Science Review  
of the proposed  
12 GeV CEBAF Upgrade

for the

Thomas Jefferson National Accelerator Facility  
(TJNAF)

*April 6-8, 2005*



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## EXECUTIVE SUMMARY

The Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (TJNAF) produces high current, highly polarized, electron beams that are utilized in experiments in three halls A, B, and C to carry out a research program that addresses the fundamental questions concerning the internal quark substructure of the nucleon and its effect in nuclei. To enhance its capabilities for nuclear physics research, TJNAF has proposed to double the energy of CEBAF to 12 GeV, upgrade the beamline to Hall A, upgrade the detector systems in halls B and C, and to build a new hall D to enhance its capabilities for nuclear physics research. The merit of the science that would become accessible with these enhanced capabilities was evaluated to be outstanding in the 2002 Nuclear Science Advisory Committee (NSAC) Long Range Plan (LRP) for Nuclear Physics that recommended the Department of Energy (DOE) proceed with this CEBAF upgrade as soon as possible. The scientific case articulated in the 2002 NSAC LRP was the primary input used in obtaining Department of Energy approval of Critical Decision 0 (CD-0) on March 31, 2004 for the 12 GeV CEBAF Upgrade project.

The Office of Nuclear Physics (ONP) conducted a Science Review of the 12 GeV Upgrade project on April 6-8, 2005 using a panel of international reviewers. The proposed science program includes three major elements: the fundamental structure of hadrons, the physics of nuclei and fundamental symmetry tests in nuclear physics. The proposed programs in each of these areas were examined to obtain a good understanding of the significance, impact and time scale for the achievement of the scientific goals for the various elements of the proposed scientific program in an international context, and of the accelerator, experimental and theoretical capabilities needed to realize the scientific goals.

This review found that the proposed research in all three areas to have high scientific merit, that all these programs require the high intensity, polarized electron beams that are unique to TJNAF and will not be possible at any other known facility in the foreseeable future, and that significant results of high scientific impact were expected to emerge from the program in both in the near and long term. A good understanding of what accelerator, experimental and theoretical capabilities are needed to achieve the various proposed scientific goals was obtained.

The overall proposed program represents an impressive coherent framework of research directed towards one of the top frontiers of contemporary science: the exploration of confinement, a unique phenomenon of the Strong Interaction, one of the four fundamental forces of nature. Investigations will be focused in large part at momentum scales interpolating between the perturbative and the nonperturbative domains of Quantum Chromo-Dynamics (QCD). Understanding the mechanisms at work in this transition region is of primary importance to our understanding of the rich variety of structures and phases that emerge out of QCD: from free quarks and gluons to hadrons and nuclei and matter under extreme conditions such as those encountered in the astrophysics of compact stars. The reviewers believe that these experimental studies are challenging, but feasible with the proposed upgrade, that they are essential to advance our

theoretical understanding of confinement and the structure of hadrons and nuclei and that they have a high probability for discoveries that may lead to significant paradigm shifts. Theoretical efforts have developed to the level where a comprehensive experimental program as presented here would significantly enhance future advancement. After a decade of research, we should know whether the formation of flux tubes by the gluon fields is the mechanism of confinement and have a significantly advanced theoretical understanding of quark-gluon systems sufficient to allow scientists to construct the first “3-D” images of the nucleon, and relate the quark structure of the nucleon to its global properties. This program requires the construction of hall D and the upgrades of halls B and C as proposed. The reviewers considered all of the proposed detector upgrades feasible and appropriate for the proposed experimental goals.

The 12 GeV Upgrade also provides a unique opportunity to use the electroweak interaction to search for physics beyond the Standard Model by performing low energy precision parity-violating measurements that are complementary to and comparable in sensitivity to searches at the Large Hadron Collider (LHC). The high intensity polarized electron beams available with the 12 GeV upgrade make possible a set of measurements that cannot be done anywhere else in the world until the construction of the International Linear Collider (ILC). This program would be sensitive to new particles at the TeV scale and probe channels not accessible with the LHC. These measurements would also provide a truly complementary technique to that above for the study of the quark structure of the nucleon. The reviewers consider this program challenging but an essential part of the overall future TJNAF science program. This program requires the proposed hall C upgrade for its initial phase and two additional large acceptance spectrometers for its longer term goals which are outside the scope of the Upgrade project. The reviewers consider the proposed phased approach of this program reasonable and the technical challenges justified.

In the foreseeable future, TJNAF, with the 12 GeV Upgrade, will be the only facility in the world using electromagnetic probes with the required kinematic reach, luminosity, and duty factor to pursue the physics goals described above. The 12 GeV Upgrade program builds strongly on previous and present accomplishments which have earned TJNAF world-wide recognition as a leader in the field. Other upcoming or planned facilities (JPARC in Japan and FAIR/PANDA at GSI in Germany) which are relevant use hadron beams and concentrate on more specialized areas of hadron physics such as systems with strange and charmed quarks.

The various experimental components of the program described above will require corresponding development of QCD based models and other theoretical techniques. The reviewers considered the ongoing theoretical development at the lab and the community to be appropriate at present but some facets of the program will require additional effort.

In the future, lattice QCD simulations on high-performance computers are expected to figure as a third major component, together with experiment and theory, driving progress in this field of research. TJNAF is optimally positioned in this area, on a worldwide scale, by the upgrade of its accelerator and detector systems in parallel with its computational capabilities. Expansion of the TJNAF Lattice QCD facility, rapid improvements of its performance and power, and further development of smart algorithms, all point in the right direction and should be continued.

The proposed program was found to represent a well-defined and truly unique set of measurements that can only be performed with the high intensity, continuous duty electron beams that have been pioneered at CEBAF. The review reaffirms the evaluation of the 2002 NSAC Long Range Plan that the science opportunity afforded by the 12 GeV upgrade is outstanding, providing the U.S. with unique world-leadership capabilities in studies of QCD and the quark structure of matter.

## INTRODUCTION

The DOE Office of Nuclear Physics (ONP) organized a Science Review of the proposed upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility in April 2005. The members of the review panel were Prof. Stanley Brodsky (Stanford University), Dr. Roy Holt (Argonne National Laboratory), Prof. Naomi Makins (University of Illinois-Urbana-Champaign), Prof. David Cassel (Cornell University), Professor Berthold Schoch (Universität Bonn, Germany), Professor Matthias Burkhardt (New Mexico State University), and Professor Wolfram Weise (Technische Universität München, Germany). Dr. Brad Tippens, Program Manager for the Medium Energy Nuclear Physics Program, chaired the review and Dr. Jehanne Simon-Gillo, Acting Director for the Facilities and Project Management Division, and Dr. Dennis Kovar, Associate Director of the Office of Science for Nuclear Physics were also present.

The 12 GeV Upgrade of the CEBAF has been proposed by TJNAF as the next technological stage of the facility to advance the laboratory's core research into hadron structure. The broad scientific questions that might be addressed by this program have been articulated in the 2002 Nuclear Science Advisory Committee (NSAC) Long Range Plan and other laboratory documents. The ONP needs to understand what scientific progress will be made in answering these questions in the near and long term and what accelerator, experimental, and theoretical capabilities will be needed to implement the proposed scientific program.

In carrying out this charge, each panel member was asked to evaluate and comment on:

- The significance and merit of specific scientific questions addressed in the 12 GeV scientific program and the feasibility of the near and long term goals for the implementation of the planned program;
- The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities;
- The theoretical efforts and technical capabilities needed in order to accomplish the planned scientific program.

The first two days consisted of presentations by the laboratory and executive sessions. These presentations provided an overview and formal response to the charge letter. The third day included a question and answer session with senior management, and panel deliberations. A brief synopsis of the reviewers' findings was presented in a closeout briefing with laboratory management and personnel on April 8, 2005. The review members were asked to submit their individual evaluations and findings in a "letter report" covering all aspects of the charge letter provided in Appendix A.

The laboratory was asked to present specific physics questions that it believes could be addressed by the research program in the first five years of running. This report is an evaluation of the program presented under that scenario. It by no means implies that the program would be complete at the end of those first five years of running.

The main report is divided into three scientific topics: Hadron Structure, Physics of Nuclei, and Fundamental Symmetries. The first and last topics correspond to the two foci discussed above. The Physics of Nuclei topic seeks to understand the role of the quark-gluon systems in the nuclear environment and is a natural extension of the Hadron Structure program.

## **Hadron Structure**

The quark structure of the proton was first discovered in the pioneering electron-proton scattering experiments at the Stanford Linear Accelerator Center (SLAC) in 1967. The deep inelastic scattering data suggested that the quark constituents of the proton were effectively pointlike, and even more remarkably, acted as if they were only weakly bound within the proton. The SLAC experiments and subsequent experiments, including meson and baryon spectroscopy, at other high energy physics laboratories were a strong motivation for the development of QCD and the theoretical discovery of asymptotic freedom, the basis of the 2004 Nobel Prize in physics.

However, despite the apparent simplicity of its basic quark and gluon interactions, QCD is an extraordinarily complex theory that cannot presently be solved analytically in the regime where quarks and gluons are confined inside bound particles called “hadrons.” The existence of quark-gluon confinement is a unique feature of the strong interaction and gives rise to all nuclear matter. The basic mechanisms which confine quarks and gluons inside hadrons and give hadrons their fundamental properties such as their mass, charge, spin, and lifetime are still not understood. To illustrate, the intrinsic masses of the three light quarks that make up the nucleon contribute only about 2% of its total mass, and the spins of the quarks contribute only about 20% of the nucleon’s spin. The long term goal of hadron structure physics has been to understand these bound systems of quarks and gluons and how the particle properties of the hadrons (mass, charge, spin, etc.) are produced by the internal quark-gluon dynamics.

Understanding these systems is critical to understanding how hadronic matter formed from the primordial quark-gluon plasma that is believed to have existed when the universe began. Toward this long term goal, the laboratory has proposed specific research that it believes could be accomplished within the first five years of running after the 12 GeV Upgrade is completed.

### **FINDINGS**

This effort is relevant to the first question in the Nuclear Physics Long Range Plan, “*What is the structure of the nucleon?*” This is a broad program involving a variety of different measurements that were presented at the review. The reviewers identified the following specific scientific questions that could be addressed in the first five years of running to be of significant importance to the advancement of understanding hadron structure:

*What is the mechanism of confinement?*

The lack of any experimental evidence for the existence of isolated quarks or gluons compels scientists to conclude that the strong interaction confines quarks and gluons to

exist only in bound systems called hadrons. Research to address this question will search for exotic meson states that would verify or reject one hypothesis for the confinement mechanism, namely the formation of gluon field “flux tubes.” This will require performing a high-statistic search for exotic mesons using a new high-intensity polarized photon beam line and a nearly total-acceptance detector.

Within the first five years of running, the GlueX collaboration proposes to establish the existence of an exotic meson state, if it exists, by identifying several of its decay modes. If none are found, it will exclude their existence at the few percent level and this will present problems for QCD as it is presently understood. Once the existence of exotics is established, subsequent data collection beyond the first five years will determine their decay modes, establish other exotic hybrid states and their family groupings in order to validate QCD predictions.

This program requires the construction of hall D that includes a tagged photon beamline and a large acceptance solenoid detector.

*Can the newly developed theoretical Generalized Parton Distribution functions that are believed to describe the quark-gluon bound systems of hadrons be experimentally determined?*

The concept of Generalized Parton Distribution (GPD) functions offers a more complete description of the partonic structure of the proton than has ever been available before. TJNAF proposes a program to determine these functions for the nucleon over a broad range of kinematics and reactions that will provide fundamentally new insights into its internal quark dynamics. In the long term, this program offers the potential for:

- determining the quark orbital angular momentum in the proton,
- determining the quark flavor contributions to the spin sum rule,
- determining the quark flavor polarization in polarized nucleons,
- constraining the light-cone wave functions of the quarks, and
- constructing “3D” images of the nucleon in the infinite momentum frame.

The laboratory claims that in the first five years of operation it will make precision measurements necessary for the partial determination of the Generalized Parton Distributions sufficient to allow for the comparison with Lattice QCD calculations, for probing the orbital motion of the quarks in the nucleon and determining the role of the transverse quark spin for several different reaction channels.

This program requires the upgrade of the CLAS detector (CLAS12) in hall B. It also requires the Super High Momentum Spectrometer (SHMS) upgrade in hall C to test the validity of factorization for the exclusive deep inelastic scattering.

*What is the asymptotic behavior of the quark structure functions in the limiting regime where the struck quark’s momentum is nearly all of the nucleon’s momentum ( $x_B \rightarrow 1$ )?*

These structure functions describe the properties of the quarks as a function of their momenta inside a hadron by assigning a probability for finding a given quark inside the nucleon with a given fractional momentum ( $x_B$ ) of the nucleon. In this “high- $x_B$ ” regime

( $0.5 < x_B < 1$ ), the behavior of the three “valence” quarks (as opposed to the gluons and “sea” quarks) is expected to dominate the dynamics inside the nucleon.

Answering this question requires measuring the unpolarized and polarized proton and neutron structure functions in the important regime of  $0.5 < x_B < 1.0$ . The laboratory proposes to measure these functions in the range of  $0.5 < x_B < 0.8$ . For the neutron structure functions, a new deuteron target technique enabling detection of the spectator nucleon (tagging) will be used to provide an unambiguous identification of the neutron.

This program requires the CLAS12 upgrade in hall B and the SHMS spectrometer in hall C.

## COMMENTS

### **The significance and merit of specific scientific questions addressed in the 12 GeV scientific program.**

*What is the mechanism of confinement?*

The unambiguous identification of several exotic mesons would be a major discovery in hadronic physics and provide substantial and unique information on the dynamics of the gluons inside the hadrons. Of the entire 12 GeV Upgrade science program, this component has the greatest potential for making an important new discovery. The experimental information concerning the spectrum of this new form of matter is an essential ingredient for the ultimate understanding of the confinement mechanism.

Spectroscopy of light mesons provides one of a very limited number of experimental techniques to explore the properties of the gluonic fields binding quarks together. Mesons are two-body bound systems of quark-antiquark pairs, making calculations easier than for three-quark systems like the nucleon. These two-body systems allow one to directly associate the quantum numbers of the gluons with the quantum numbers of the meson itself, unlike the three-quark systems. The observation of exotic mesons with quantum numbers forbidden for regular mesons would indicate excitations of the gluon fields that scientists could use to extract the contribution of the gluons to the meson’s mass, spin, and parity. This information would provide a powerful constraint on QCD based calculations and directly test the conjecture that the self-interacting gluon fields form a “flux tube” between the quark-antiquark pair.

Previous searches using meson beams or protons to produce these states have been inconclusive. There are reasons to think that photons could be more effective at producing these states but this capability has been unavailable prior to the 12 GeV Upgrade.

*Can the newly developed theoretical Generalized Parton Distribution functions that are believed to describe the quark-gluon bound systems be experimentally determined?*

Recent theoretical advances have established, within the framework of QCD, the concept of Generalized Parton Distributions (GPDs), which are accessible through deeply-virtual exclusive reactions. These GPDs describe the correlations between quark-states of different momenta within the nucleon, and thus reach beyond the “ordinary” parton

structure functions. They provide, among other properties, a simultaneous determination of the longitudinal momenta and transverse position of quarks within the nucleon. For the first time “three-dimensional” (two spatial dimensions, one momentum dimension) pictures of the proton and neutron could be constructed from experimental measurements.

The experimental determination of these functions has tremendous potential to provide a quantitative description of the quark motion inside hadrons, specifically the light-cone quark wave functions. The GPDs will allow scientists to relate the quarks’ motion to the static properties of the nucleon such as the average charge and magnetic distributions and the quark angular momentum contribution to the spin of the nucleon. The latter, together with the gluon contribution, is important for determining the origin of the nucleon’s spin, a major goal of nuclear physics.

*What is the asymptotic behavior of the quark structure functions in the limiting regime where the struck quark’s momentum is nearly all of the nucleon’s momentum ( $x_B \rightarrow 1$ )?*

The high beam intensity combined with the 12 GeV energy of CEBAF will provide a unique opportunity for scientists to measure the quark polarized structure functions in a previously inaccessible kinematic regime where the valence quark contributions dominate over the gluon and sea-quark contributions. These measurements will test a prediction derived from the basic interactions of QCD that the ratio of the spin anti-parallel quark distribution to the spin-parallel distribution should fall as  $(1 - x_B)^2$  as  $x_B$  approaches 1. The CEBAF measurements would provide sufficient accuracy to verify or reject this prediction. If the asymptotic dependence disagrees with the QCD prediction, it would raise serious questions about the behavior of QCD in confined quark systems. Currently, the asymptotic behavior of the pion structure function indicates a possible discrepancy with QCD. If these data hold up under further scrutiny, this represents a serious breakdown in our understanding of how to apply QCD or in QCD itself. Thus, there could be more surprises when precise data from this program become available for the nucleon. The  $d/u$  ratio and  $A_1$  measurements are particularly important for these studies.

### **The feasibility of the near and long term goals for the implementation of the planned program.**

*What is the mechanism of confinement?*

The search for exotic mesons predicted by lattice gauge calculations in the 2 GeV mass range appears feasible based on the design presented at the review. The approach presented of employing a 9 GeV polarized tagged photon beam and a large acceptance solenoidal detector is considered a sound approach and has been internally reviewed by the laboratory. The 9 GeV photon beam requires a 12 GeV electron beam which sets the energy of the proposed upgrade.

The detector must be as hermetic ( $4\pi$  solid angle coverage) as possible with sufficient resolution so that all the particles that are produced (charged and neutral) can be detected and identified to reconstruct all the mesons that are produced in any given event. Simulation data presented during the review indicated that the design of the detector provides uniform acceptance exceeding 90% over the entire azimuthal angular range and within the polar angular range  $-25^\circ > \theta > 25^\circ$  with the acceptance falling to 80% as the

polar angle approaches  $0^\circ$  and  $180^\circ$ . A 2 Tesla magnetic field provides the detector with momentum measurement capability for the charged particles. Information of angular and energy resolution for both charged and neutral particles was not provided. Data rates using about  $10^8$  photons/sec were estimated to be about 15 kHz after the level 1 trigger which leads to about 1 PetaByte/year of data. This is a formidable rate, but technically feasible to handle. The design was considered to be feasible, but it is clear that a more detailed simulation of the detector is necessary and a careful technical design review needs to be done before complete feasibility of the experimental design can be evaluated.

The development of sophisticated Partial Wave Analysis (PWA) software is required to provide unambiguous identification of the exotic mesons. Significant progress in the development of this software was demonstrated by the GlueX collaboration. The knowledge of the photon polarization can be used to simplify the PWA and access additional information on the production mechanism, so a tagged polarized photon beam is essential for identification of these mesons. The collaboration is encouraged to continue its development of PWA software combined with realistic Monte Carlo simulations of the detector. The PWA software should include theoretical assumptions of meson and baryon production that go beyond the present isobar mechanism.

*Can the newly developed theoretical Generalized Parton Distribution functions that are believed to describe the quark-gluon bound systems be experimentally determined?*

Given the equipment envisioned for the upgrade, these experiments appear to be feasible. The SHMS is essential for the deep exclusive experiments that are necessary to test the validity of factorization for both pion and kaon electroproduction. The CLAS12 is essential for the deeply virtual Compton experiment. The CLAS12, being a new detector design, should be given a technical review.

Given the very recent development of the GPD formalism, more investigations on the range of its validity have to be undertaken. The interpretation of observables in exclusive and semi-inclusive scattering in the deeply virtual regime depends on the validity of factorization theorems. The corresponding domains of validity will have to be explored systematically. Furthermore, the application or use of GPDs, as well as of the improved knowledge of the standard parton distribution functions, in other areas of particle and nuclear physics should be investigated and illustrated.

*What is the asymptotic behavior of the quark structure functions in the limiting regime where the struck quark's momentum is nearly all of the nucleon's momentum ( $x_B \rightarrow 1$ )?*

These experiments appear to be feasible with the 12 GeV electron beam plus the upgraded JLAB detectors CLAS12 and SHMS. The polarized neutron measurements will be performed using a polarized  $^3\text{He}$  target. The separation of  $u$  and  $d$  quarks in a neutron can be done with an unpolarized deuterium target together with detection of the recoil spectator nucleon. The required validation of the spectator nucleon method will be carried out in the near future.

The proposed SHMS spectrometer is absolutely necessary for the semi-inclusive deep inelastic scattering tests of factorization. The use of single pions to tag the quark flavor requires the assumption that the scattering process and the subsequent hadronization process can be separated. This assumption must be explored experimentally to validate

the flavor-separated data. This involves studies over a large range of kinematic variables of  $x_B$ ,  $z$  and  $Q^2$ . These studies have been carried out at 6 GeV in hall C and indicate that factorization holds up to an  $x_B$  and  $z$  of approximately 0.5. It is plausible with the high luminosity 11-GeV beam, the HMS and the SHMS that the factorization tests can be performed in a reasonable amount of time over a large  $x_B$  and  $z$  range.

**The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities.**

*What is the mechanism of confinement?*

The unambiguous discovery of hybrid mesons will have a fundamental and significant impact on our understanding of the role of gluons in hadrons. In addition, failure to do this program will leave a major gap in our understanding of the existing light meson spectrum in general and in the photoproduction of mesons in particular. The discovery of exotic mesons would give confidence in QCD calculations of the meson spectrum and characterize the formation of these gluon field “flux tubes.” It would strongly support the idea that these structures are the origin of confinement. The failure to find these states would require serious rethinking of our understanding of QCD calculations in the non-perturbative regime.

Current experiments that are relevant to this research are the PANDA experiment at Gesellschaft für Schwerionenforschung mbH (GSI) in Germany and the CLEO-c experiment at Cornell. These experiments are looking for pure glue states and hybrid meson states primarily involving heavy quarks while the TJNAF program will focus on states with exotic quantum numbers. CLEO-c is presently scheduled to terminate operations by 2009 and will not be in operation when the upgrade is implemented. The PANDA experiment uses hadron production which is believed to be less sensitive than photo-production for producing such states.

*Can the newly developed theoretical Generalized Parton Distribution functions that are believed to describe the quark-gluon bound systems be experimentally determined?*

The JLab 12 GeV Upgrade will permit a thorough feasibility study of the GPD program. The first 5 years of running with an upgraded CLAS target and detector should yield specific information about the GPDs along the curve  $x = \xi$  and at various values of  $Q^2$  and  $t$  in kinematic space via Deeply Virtual Compton Scattering (DVCS) data and integrated information on the GPDs via DVCS cross-section measurements. The DVCS spin asymmetry and cross-section measurements will cover about half the range in  $\xi$  ( $0 - 1$ ) from 0.05 - 0.5. These measurements will constrain models of the GPDs sufficient to provide good sensitivity to the total  $u$ -quark angular momentum and the transverse spatial distribution of quarks in the valence region, as they are parametrized in those models. If current data from the 6 GeV program verifies that factorization holds for hard-exclusive meson production, then information on GPDs and light-cone wave functions for individual quark flavors will also be provided by the first 5 years of data at 12 GeV. Furthermore, GPDs are a relatively new concept and it is highly likely that additional physical information beyond what has been mentioned in this report can be related to GPDs.

Related experiments are planned or underway at COMPASS and HERMES, although their impact is significantly restricted in kinematic extent and beam luminosity, whereas the planned JLab program will extend well out to the valence quark region, up to  $x = 0.76$  and  $Q^2 = 10 \text{ (GeV/c)}^2$  and with the beam luminosity required to obtain sufficient statistical precision. The JLab effort is unique in its coverage of kinematics (with high statistics), scope of reaction channels and polarization observables.

*What is the asymptotic behavior of the quark structure functions in the limiting regime where the struck quark's momentum is nearly all of the nucleon's momentum ( $x_B \rightarrow 1$ )?*

The measurements of the quark structure functions will provide precise measurements of the fundamental spin and flavor structure of nucleons. If the perturbative QCD prediction is validated it will provide confidence in using such methods in other contexts. In particular, the measurements at large  $x_B$  can decisively determine the applicability of perturbative QCD analyses in this kinematic region of the nucleon.

The degree of impact, however, will depend on how high in  $x_B$  the measurements can be made. As  $x_B$  approaches 1, higher twist effects begin to dominate; but these effects are expected to be suppressed at large  $Q^2$ . Measurements over a range of  $Q^2$  as well as measurements involving longitudinal-transverse separation are planned to control these effects.

### **The theoretical efforts and technical capabilities needed in order to accomplish the planned scientific program.**

*What is the mechanism of confinement?*

The major theoretical effort with this program is the development of the PWA software. The exotic mesons can couple to the multi-meson continuum even though they have unusual quantum numbers. This will complicate the PWA. The present PWA assumes an isobar model for meson processes. Theoretical effort is needed to develop more advanced methods that are not limited by the isobar assumptions. Development of lattice QCD calculations that can estimate the mass spectrum and partial widths of the exotic states needs to be vigorously pursued.

Technically, the construction of hall D and a new detector is absolutely essential for the success of this program. The existing CLAS detector could not be modified to accommodate this program. The extra half loop through the accelerator provides the necessary 12 GeV electron beam required to generate a photon beam of sufficient energy to produce the exotic mesons in the expected mass region. The nearly hermetic detector is a unique design that has been optimized for photo-production. A full technical review of the GlueX design needs to be done.

*Can the newly developed theoretical Generalized Parton Distribution functions that are believed to describe the quark-gluon bound systems be experimentally determined?*

The near term DVCS data from the 12 GeV program will be analyzed within the context of GPD model parameterizations. To exploit these data maximally, it is important to fully explore all model-independent, theoretical constraints that can be placed on these new functions. This work is being intensely pursued at present, and must continue. Also, it is important to use lattice calculations and other approaches to QCD to help guide the

construction of theoretical GPD parametrizations. In terms of the light-front wave functions one must include transitions involving change of parton number, which will require modeling higher Fock components.

The increase in luminosity by a factor of 10 proposed for the upgrade project is absolutely essential for this component of the science program. It makes possible particle identification and momentum determination of particles up to the maximum beam energy, and increased acceptance to forward production angles. The Double DVCS (DDVCS) cross-sections are two to three orders of magnitude smaller than those for DVCS requiring longer running periods and increased luminosity. They would allow an unintegrated or more direct determination of the GPDs over a range in  $x$  and  $\xi$  of approximately  $-0.5 < x < 0.5$  and  $0.05 < \xi < 0.5$

*What is the asymptotic behavior of the quark structure functions in the limiting regime where the struck quark's momentum is nearly all of the nucleon's momentum ( $x_B \rightarrow 1$ )?*

The precise interpretation of the deeply inelastic scattering data involves knowledge of radiative corrections, and the flavor-tagged measurements require detailed knowledge of the quark fragmentation functions. There are possible corrections from the non-additive properties of the deuteron itself, such as hidden-color and meson exchange currents.

Lattice gauge theory is now beginning to provide predictions for observables which are relevant to the experimental program discussed here. With time, improved actions and increasing computer power, accurate simulations of observables are anticipated at smaller quark masses which permit reliable extrapolations. It is thus anticipated that the JLab experimental results will provide incisive tests of lattice gauge theory predictions.

In addition to lattice gauge calculations, other theoretical approaches should be pursued to enhance our ability to interpret these data. For example, light-cone or Schwinger-Dyson approaches to QCD, although at present having a less rigorous foundation than lattice QCD, offer the opportunity to elucidate the physics of hadron structure from a complementary approach which will be valuable in these high momentum transfer experiments.

## Physics of Nuclei

### FINDINGS

This program seeks to address the question, “*How does the known phenomenological description of nuclei as nucleons interacting via meson exchange arise from the underlying dynamics of quarks and gluons described by QCD?*” This is a long term program that seeks to combine the knowledge gained from the Hadron Structure program with a specific set of measurements from this program to understand the nuclear interaction in terms of QCD. This work is relevant to the second question in the 2002 Nuclear Physics Long Range Plan, “*What is the structure of nucleonic matter?*” For the first five years of running, this program would focus on two aspects of this problem:

- Understanding the origin of the modification of parton structure functions in the nuclear medium (EMC effect), and

- Understanding the evolution of quark propagation in nuclei and the mechanisms of how energetic, scattered quarks interact with their environment to confine themselves inside hadrons (hadronization).

The EMC effect will be studied by focusing on precision measurements in the valence quark region of  $x_B < 1$ , perform structure function measurements in light nuclei for  $x_B > 1$  to search for “hidden color” effects, first studies of changes to the nucleon’s spin structure in a nuclear environment, and the study of the spin-dependence of the antishadowing effect. The evolution of quark propagation in nuclei and the hadronization mechanisms will be studied by measuring the A-dependence of Semi-Inclusive and Polarized Deeply Inelastic Scattering.

This program requires the new magnets, Cerenkov counter, and forward detector associated with the CLAS12 detector in hall B and the High Momentum Spectrometer (HMS) in hall C. The Super High Momentum Spectrometer (SHMS) of hall C would be advantageous, but not required. Polarized light nuclear targets will be necessary.

### COMMENTS

#### **The significance and merit of specific scientific questions addressed in the 12 GeV scientific program.**

The increased beam energy and intensity provided by the 12 GeV Upgrade open up a kinematic regime for these studies which has not been available to scientists previously.

The observation that the quark momentum distribution of a free nucleon is significantly modified when inside a nucleus, ‘EMC effect’, has been a long standing issue in nuclear physics and is not understood. In heavy nuclei, there is essentially a universal shape to the modification of this distribution. The present program will characterize how the ‘EMC effect’ evolves from deuterium to heavy nuclei by performing measurements on light nuclei such as  $^3\text{He}$  and  $^4\text{He}$  where the nuclear density is changing significantly. In addition, the observation of a “spin EMC effect” would provide us with valuable information on the nature of the coupling of the nuclear medium to the nucleon. For these reasons and because exact quantum Monte Carlo calculations can be performed for these nuclei, high accuracy studies of these nuclei are essential for understanding this phenomenon.

The process of “hadronization”, the observed behavior that as a struck quark emerges from a collision it always binds with other quarks, can only be parameterized. This process dominates much of the interactions of hadrons with themselves and other particles. Constructing such functions is an essential goal in understanding hadron, and specifically nucleon, structure. The precise knowledge of the hadronization processes in nuclear matter is required to extract fragmentation functions in combination with the information derived from deeply inelastic scattering. A better understanding of these processes would be valuable to research outside this field such as the heavy ion program at the Relativistic Heavy Ion Collider (RHIC).

**The feasibility of the near and long term goals for the implementation of the planned program.**

These experiments require the 11 GeV beam energy and high intensity planned for the existing Halls. The CLAS12 will be necessary for the quark propagation studies while the SHMS will be essential for color transparency experiments involving a pion or proton in the final state. Starting with  $^3\text{He}$  and  $^4\text{He}$  targets is an excellent choice motivated by the existing microscopic theory for those nuclei. The measurements of  $g_1^A(x)$  with polarized nuclear targets will be first performed on  $^7\text{Li}$ , taking advantage of the high degree of polarization achieved with this target. It is not clear whether flavor tagging (quark species identification) can be used in nuclei because at 11 GeV the quarks are still likely to fragment inside the nucleus. However, this only means that flavor separation may not be unambiguously possible, but this does not affect the ability of the planned experiments to determine the EMC effect without flavor separation.

**The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities.**

The role of quarks as an essential degree of freedom in nuclei will be established in an unambiguous way. The traditional picture of nuclei in terms of nucleons interacting through phenomenological potentials will undergo radical changes by establishing the connection towards the underlying QCD.

There are no other programs to study the EMC effect worldwide. A low statistics measurement on  $^{14}\text{N}$  and  $^{84}\text{Kr}$  has recently been performed with HERMES at the Deutsches Elektronen-Synchrotron (DESY) in Germany. The HERMES data are limited by luminosity and selection of targets. The expected CLAS12 data will set the standard and provide definitive results for quark propagation. No other program is expected to provide the required data to understand the EMC effect in nuclei.

Results from the proposed 12 GeV measurements could be important for interpretation of experiments at other facilities like HERA at DESY, the RHIC at BNL, and even the Large Hadron Collider (LHC) at CERN.

**The theoretical efforts and technical capabilities needed in order to accomplish the planned scientific program.**

The theory for the light nuclei –  $^3\text{He}$ ,  $^3\text{H}$  and  $^4\text{He}$  – is well developed in terms of microscopic calculations. This will enable one to separate nuclear structure effects from modifications of the nucleon structure, however, continued support for using exact Monte Carlo calculations in the Deeply Inelastic Scattering (DIS) regime will be essential. Theoretical development aimed at understanding the time evolution of hadronization will also be essential. Issues of factorization in the extraction of fragmentation functions from the semi-inclusive experiments must be addressed before one could reach firm conclusions from these measurements.

More QCD-based work, rather than just QCD-inspired models, needs to be done on Parton Distribution Functions (PDF) in nuclei, in particular for  $x_B > 1$ , to fully exploit the potential insights that are to be gained from this program. These observables are not

presently within reach for lattice gauge calculations, so other, continuum-based approaches to QCD need to be further developed.

This program requires the upgrade of hall B and the construction of polarized nuclear targets. The upgrade of hall C is required for the color transparency measurements.

## Fundamental Symmetries

The Standard Model of strong and electroweak interactions has been surprisingly successful in describing a broad range of phenomena in nuclear and particle physics. It is amenable to tests at the Z pole and high-energy searches for new particles not allowed in the Standard Model, particularly supersymmetric particles anticipated at the Large Hadron Collider (LHC).

It is also now widely appreciated that the Standard Model is amenable to tests at low energy. These include neutrino physics, atomic parity violation and searches for double beta decay and electric dipole moments. The recent discovery of neutrino mixing is stimulating an increase of research in testing the Standard Model in the lepton sector. Precision low-energy measurements of experimental deviations from Standard Model predictions can signal the existence of new particles at a mass scale comparable to that of the LHC. The 12 GeV Upgrade will provide electron beams with the right combination of energy, polarization, and intensity that open the potential for such low energy tests using electron parity-violating scattering. While not part of the original 12 GeV Upgrade science program, the laboratory has proposed a long range program of parity-violating experiments that can be divided into near term (the first five years), mid term, and long term projects.

### FINDINGS

This program seeks to address the 2002 Nuclear Physics Long Range Plan question, “*What is to be the new Standard Model?*” The laboratory has proposed a set of low-energy parity-violating (PV) electron scattering measurements with sufficient accuracy to be sensitive to effects of new physics at the TeV scale. Only the near term goal is within the scope of the 12 GeV Upgrade project, the mid and long term goals will require equipment beyond the scope of the 12 GeV project.

**Near Term Goal:** Measure the asymmetry in parity-violating deeply inelastic scattering from the deuteron to extract the axial-vector neutral boson couplings to the light quarks ( $2C_{2u} - C_{2d}$ ) with a factor of 20 improvement over the present measurements.

**Mid Term Goal:** Highly accurate measurements of asymmetries in parity-violating deep inelastic scattering from the deuteron and proton using a large acceptance spectrometer to:

- Determine the  $d/u$  ratio at high  $x$ ,
- Set a limit on isospin and strangeness symmetry violations at the partonic level, and
- Study higher-order spin effects in parity-violating asymmetry measurements.

**Long Term Goal:** High profile measurement of the asymmetry in parity-violating electron-electron scattering. The goal of this experiment is to yield a clean measurement at the same level of accuracy as the Large Electron Positron Collider (LEP) measurements at CERN.

## COMMENTS

### **The significance and merit of specific scientific questions addressed in the 12 GeV scientific program.**

These experiments are important for constraining whether any new physics outside of the current Standard Model exists, even after the LHC produces its first results. In addition, these measurements will provide a highly accurate determination of the structure functions for the proton at high  $x$  that will nicely complement the hadron structure program.

In the near term, the Parity-Violating Deeply Inelastic Scattering (PVDIS) measurements will permit extraction of the weak neutral boson coupling to the light quarks with an improvement in accuracy of the existing measurements of at least a factor of 20. A measurement of this accuracy would help resolve the current disagreement of the NuTeV determination of the weak mixing angle with the Standard Model prediction. It could also constrain possible new physics beyond the Standard Model.

The precise determination of the quark distribution ratio  $d/u$  at large  $x_B$  could resolve the shape of the parton distribution in the valence quark region. On a nuclear target, these measurements can test whether the anti-shadowing phenomena is the same for weak and electromagnetic currents; recent theoretical work indicates that anti-shadowing is not universal.

In the longer term, a high-profile measurement of the asymmetry in parity violating Möller scattering is planned. This measurement could probe for new physics at the 25 TeV scale, representing a complementary effort to the scientific program at LHC that could provide valuable information on extensions to the Standard Model even after the LHC is running.

### **The feasibility of the near and long term goals for the implementation of the planned program.**

The expected asymmetry in PVDIS from the deuteron is relatively large,  $10^{-4} Q^2/\text{GeV}^2$  and it is feasible to measure the asymmetry with an accuracy of less than 1% using the HMS and SHMS spectrometers. Experiments of comparable accuracy have already been demonstrated at JLab. A technical challenge will be improving the Compton polarimeter to achieve measurements with an error of less than 1%. Work on this issue is underway within the present 6 GeV program. The nucleon structure studies will require a special toroidal spectrometer that is not part of the current 12 GeV Upgrade project.

For the long term, the Möller scattering experiment must measure the asymmetry to 0.6 ppb, a factor of 24 better than the existing SLAC measurement. The experiment will require target development to handle 5 kW of beam power and a special spectrometer and

detectors. The 5-kW power in the target could lead to significant fluctuations. Linearity of the electronics is an issue. Novel technical developments will be necessary before this experiment can be performed.

**The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities.**

This experimental program is one of the outstanding highlights of the 12 GeV Upgrade project. This science cannot be performed elsewhere in the world; it requires the beam intensity, polarization, and quality that presently can only be produced at TJNAF.

Without the PVDIS experiments, important information needed to understand the NuTeV anomaly will not be obtained, and the opportunity to obtain precision values for the  $C_2$  couplings to  $u$ - and  $d$ -quarks that would probe for new physics at the TeV scale will be lost.

The Möller scattering experiment would probe for new physics at the 25 TeV scale. An experiment of this accuracy has the potential for either discovery of new physics, say a new Z boson, or assisting the LHC experiments in pinning down the parameters of a possible supersymmetric theory. No other existing or planned facility, short of the International Linear Collider (ILC), can provide data that would have such an impact.

**The theoretical efforts and technical capabilities needed in order to accomplish the planned scientific program.**

Theoretical support is required in order to understand higher order and charge-symmetry-breaking effects at the partonic level in order to extract the combination  $2C_{2u} - C_{2d}$  at the required level of precision.

The technical capabilities needed for the near term goal include the HMS in hall C and a 60 cm liquid deuterium target. The SHMS would reduce the beam time for this experiment by a factor of two and provide additional systematic error checks. A detailed assessment should be carried out concerning the accuracy that can be achieved for the input parton distributions.

For the mid term, a special large acceptance spectrometer is required for the nucleon structure measurements. Detectors with good  $\pi/e$  separation at high counting rates have to be developed.

For the long term, the Möller scattering experiment will require the development of a challenging 150 cm, high power 5 kW liquid hydrogen target and a special toroidal spectrometer with new radiation-hard, integrating detectors and electronics. R & D aimed at the technical issues of the target and electronics should be proposed.

The additional hardware required for the mid and long term goals are not part of the proposed 12 GeV upgrade and would require separate funding.

## Summary

The laboratory has proposed research for the 12 GeV Upgrade in three major areas of research: Hadron Structure, Physics of Nuclei, and Fundamental Symmetries. These programs all require the high intensity, polarized electron beams that are unique to TJNAF and will not be possible at any other known facility in the foreseeable future. Scientific topics for each of these programs that were considered feasible using the proposed equipment for the upgrade and that should produce definitive results in the first five years of running were identified by the reviewers.

The proposed program in Hadron Structure requires the construction of hall D for the exotic meson search and the upgrade of Hall B for the nucleon structure studies. The hall C upgrade is necessary for verifying the validity of factorization for the exclusive scattering. The Hadron Structure program is broad in its scope and will have a significant impact in advancing our knowledge of the quark structure of matter in the confinement regime of QCD. The 12 GeV Upgrade will make TJNAF the world center for research in this area for at least a decade following start of operations of the upgrade project. This program requires the theoretical development of lattice QCD technology to take full advantage of the experimental program. The reviewers considered the laboratory's present development in this area appropriate to meet the needs of the program, but encouraged the laboratory to press the development of both lattice QCD capability as well as conventional theory.

Based on the results of this review, one could expect the following impact on the field in a 10 year time scale. During the first five year period, the existence of the predicted exotic meson states should be confirmed or rejected. The methodology for determining the Generalized Parton Distribution functions would be validated and specific sections of these functions determined from data. The asymptotic behavior of the valence quark structure functions will be determined which will provide theorists with important constraints on how QCD works in the confinement regime. During the latter five year period, more exotic meson states, if they exist, should be identified. Information from these different states will allow scientists to determine the properties of the gluons binding the quarks which will confirm or reject the "flux tube" hypothesis for the confinement mechanism. Resolving this question would be a major achievement in the field. As development of the Generalized Parton Distribution functions matures, the first "3-D" images of the nucleon would emerge and new information on quark structure would be generated, such as the quark angular momentum which is important for understanding the origin of the nucleon spin. Lattice gauge calculations will continue to be developed to a level where these calculations will be tested directly by the data and will play a critical role in understanding gluon binding and the development of the quark wave functions.

The Physics of Nuclei program requires the hall B upgrade. The hall C upgrade is needed for the color transparency measurements. This is a long term program that will require significant theoretical support. The reviewers considered the two topics proposed for the first five years of running, the "EMC effect" and "hadronization", to be significant for the field and unique to TJNAF. The first is to understand the cause of the known phenomenon that the quark motion inside a free nucleon and one bound in a nucleus are

universally different. Understanding this phenomenon is important for it directly connects the individual nucleon's quark dynamics to the collective nucleus. The second effort is to understand the process of hadronization, in which an energetically struck quark binds with other quarks to reconfine itself inside a hadron. This process can only be parameterized and is not understood in a fundamental way. Knowledge gained from this program would advance our theoretical understanding of this process that would have application beyond this program in other research such as the RHIC search for and characterization of the quark-gluon plasma.

The program in Fundamental Symmetries will employ the technique of parity violating electron scattering to search for new physics beyond the Standard Model. It requires the high quality, high intensity, polarized electron beams unique to TJNAF. This is a challenging program with the potential of discovering new physics. At a minimum, the program would provide new very precise data on the weak neutral current interactions that, combined with the LHC program, would provide constraints on new particles at the TeV mass scale. Without the 12 GeV Upgrade, this program could not be done anywhere in the world today. It is considered important for its discovery potential. The initial experiment would not require anything beyond the hall C upgrade. The second and third phases of the program are outside the scope of the 12 GeV project and will require a new large acceptance spectrometer for the deeply inelastic scattering experiments and a special solenoidal spectrometer together with a 5 kW target for the electron-electron scattering experiment.

## Appendix A: Charge Letter

Dr. Christoph Leemann  
Director  
Thomas Jefferson National  
Accelerator Laboratory  
12000 Jefferson Avenue  
Newport News, VA 23606

Dear Dr. Leemann:

On April 6-8, 2005, the DOE Office of Nuclear Physics will conduct a Science Review of the proposed Continuous Electron Beam Accelerator Facility (CEBAF) 12 GeV Upgrade Project at Thomas Jefferson National Laboratory (TJNAF). The primary purpose of the review is to understand the merit and significance of the planned scientific program with the CEBAF 12 GeV Upgrade in the context of current and planned world-wide capabilities. The scientific questions that might be addressed by this program have been articulated in the 2002 NSAC Long Range Plan and other documents that have been generated. This office would like to understand what scientific progress will be made in answering these questions in the near and long term and what accelerator, experimental, and theoretical capabilities will be needed to implement the proposed scientific program.

In carrying out this charge, each panel member is asked to evaluate and comment on:

- The significance and merit of specific scientific questions addressed in the 12 GeV scientific program and the feasibility of the near and long term goals for the implementation of the planned program;
- The impact of the planned scientific program on the advancement of nuclear physics in the context of current and planned world-wide capabilities;
- The theoretical efforts and technical capabilities needed in order to accomplish the planned scientific program.

The first two days will consist of presentations by the laboratory and executive sessions. The third morning will be used for an executive session and preliminary report writing; a brief close-out will take place in the early afternoon. Preliminary findings, comments, and recommendations will be presented at the close-out. A draft agenda is enclosed.

The contact within this office for the review is Dr. Brad Tippens at (301) 903-3904, or E-mail: [brad.tippens@science.doe.gov](mailto:brad.tippens@science.doe.gov). The reviewers have been instructed to contact Theresa Foremaster at TJNAF, (757) 269-7883 or E-mail: [HYPERLINK "mailto:formast@jlab.org" formast@jlab.org](mailto:formast@jlab.org) regarding any logistics questions. Word processing and secretarial assistance should be made available during the review. A list of background materials to be provided to the reviewers is enclosed. Note that only the indicated items are to be sent as hard copies. The other items are provided to the reviewers as links only.

A list of the review participants is enclosed. Each panel member is being asked to comment on all aspects of the review charge. They will be asked to write individual “letter reports” on their findings. The Chairman will accumulate these “letter reports” and compose a DOE report based on the information in the letters.

I greatly appreciate your efforts in preparing to present your laboratory’s plans regarding the scientific program of the 12 GeV Upgrade. It is an important process that allows our office to understand the significance, feasibility, and implementation of the planned science program. I look forward to a very informative and stimulating visit.

Sincerely,

Dennis Kovar

Associate Director of the Office of Science  
for Nuclear Physics