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March 28, 2003

Christoph W. Leemann
Director
Thomas Jefferson National Accelerator Facility
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Dear Chris,

Enclosed with this letter is a copy of the JLab PAC XXIII report entitled a "Review of the Physics Motivation for the JLab 12 GeV Upgrade".

As you requested, the JLab Program Advisory Committee, at its most recent meeting, evaluated the science that is driving the proposed JLab upgrade. The PAC held an extended meeting on January 17-22, 2003 with an enlarged membership to respond to the charge. The agenda included extended discussions with the JLab User community, the staff , and your Laboratory management. The Committee then held several days of review and discussion of the scope of the science program, its impact, the accelerator capability and the instrumentation needed to address the objectives of the physics program.

The PAC reviewed the content, impact, and the formulation of the scientific case being developed in the context of the upgraded experimental facility with its new capabilities and much greater technical reach than has heretofore been possible.

This report gives the PAC assessment of the new physics opportunities at 12 GeV including a topic-by-topic evaluation of the research in each area of the program, its match to the experimental facilities, and an assessment on how well both of these have been formulated in the JLab reports to date. These findings by the Committee are embedded in four recommendations to the JLab research community.

Overall it is the judgment of the PAC that the envisioned JLab Upgrade offers an outstanding opportunity for exploring new and fundamental physics issues of strong interest to the community of nuclear and particle physicists. In many respects the new experimental facilities will be unique in the world. They will also impact issues raised at other facilities. Therefore the PAC enthusiastically endorses the JLab 12 GeV Upgrade in view of the timeliness and high impact it can have on physics issues of concern to a broad spectrum of the nuclear and particle physics community.

Chris, we members of the PAC are extremely enthusiastic about the physics impact that this upgrade will have on the JLab research program. We wish you every success in bringing this important initiative to a successful conclusion.

In addition I want to thank you, Larry Cardman, your Hall Leaders and staff, and all the JLab Users, who have worked so hard to develop this vision of JLab's future, for all your input and comments during the process of this review. A very compelling and exciting program has been identified. Furthermore, I would like to thank Clara Perdue, Shauna Cannella, Sue Ewing, and Myung Bang for their help and support in making the PAC XXIII meeting run so smoothly and efficiently.

With best regards,

Peter D. Barnes
Chairman, PAC XXIII

PAC XXIII
Review of the Physics Motivation for the JLab 12 GeV Upgrade

March 28, 2003

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Executive Summary

The Jefferson Lab management, Staff, and User community have been actively developing a vision for the evolution of the research program at the Continuous Electron Beam Accelerator Facility, CEBAF. Building on the success and productivity of the current program they have identified a coherent set of science issues that could be addressed with a 12 GeV electron beam together with an upgraded experimental research capability. These ideas and goals have been further developed in a series of workshops and reports, which altogether, define a new 12 GeV research program.

The Laboratory management has charged the JLab Program Advisory Committee, PAC, to make an evaluation of the science that is driving this proposed upgrade, to identify additional research opportunities, and to analyze the match between the physics agenda and the experimental capabilities planned for the upgraded facility. As formulated, the facility upgrade plan envisions a doubling of the electron beam energy, a new experimental hall, Hall D, with a hermetic detector for addressing tagged photon physics, and significant enhancements to the spectrometers and detectors in the existing Halls A, B, and C.

The PAC met on January 17 - 22, 2003 with an enlarged membership, to respond to this charge. The agenda included extended discussions with the JLab User community, the scientific staff, and the Laboratory management. The Committee then held several days of review and discussion of the scope of the physics program, its impact, and the accelerator/instruments needed to address this physics program.

This report gives the PAC assessment of the new physics opportunities at 12 GeV including a topic-by-topic evaluation of the research in each area of the program, its match to the experimental facilities, and an assessment on how well both of these have been formulated in the JLab reports to date. These findings by the Committee are embedded in the following four recommendations to the JLab management:

Recommendation #1
The PAC recommends that

a) *Gluonic excitations of mesons and the origin of confinement, and*

b) *The unified description of the quark-gluon structure of the nucleon, primarily through the determination of Generalized Parton Distributions*

continue to represent the main driving motivations for the 12 GeV upgrade. The physics is well motivated and JLab has a unique opportunity to have strong impact in these areas.

Two additional areas have outstanding potential to develop into major components of the physics program.

Recommendation #2
The PAC recommends that the JLab management, staff, and User Community continue to define and formulate a coherent experimental and theoretical physics program to develop a unified description of high-density cold nuclear matter as it can be explored at the 12 GeV facility,

Recommendation #3
The PAC recommends that the JLab management, staff, and User Community continue an aggressive study of the feasibility and technical requirements for measurements that test the Standard Model: in the electro-weak sector as they relate to parity violation in deep-inelastic scattering, and the weak charge of the proton and the electron, as well as in the strong sector as they test the strong interaction Lagrangian through investigation of the radiative decay of π^0, η, *and* η' *mesons.*

Recommendation #4
The PAC endorses the overall plan for the major new instrumentation as being required to implement the new physics program and therefore recommends that the major components in all four halls be implemented.

Specific suggestions regarding other research areas and instrumentation are included in the body of the PAC report.

Overall it is the judgment of the PAC that the envisioned JLab Upgrade offers an outstanding opportunity for exploring new and fundamental physics issues of wide spread interest to the community of nuclear and particle physicists. In many respects the new experimental facilities will be unique in the world. They will also impact issues raised at other facilities. Therefore the PAC enthusiastically endorses the JLab 12 GeV Upgrade in view of the timeliness and high impact it can have on physics issues of concern to a broad spectrum of the nuclear and particle physics community.

PAC XXIII
Review of the Physics Motivation for the JLab 12 GeV Upgrade

I. Introduction

The Jefferson Lab management, staff, and User community have been actively developing a vision for the evolution of the research program at this unique electron accelerator facility. Building on the success and productivity of the current program they have identified a coherent set of science issues that could be addressed with a 12 GeV high current electron beam in combination with a new and upgraded experimental research capability. These ideas and goals have been further developed in a series of workshops and reports as listed in Appendix A of this report.

The facility upgrade plan envisions a doubling of the electron beam energy, a new experimental hall with a hermetic detector for addressing tagged photon physics, and significant enhancements to the spectrometers and detectors in the existing Halls A, B, and C.

In response to a request by the Laboratory management, the JLab Program Advisory Committee, PAC, used a major part of the extended PAC XXIII meeting to evaluate the science that is driving this proposed upgrade, to identify additional research opportunities, and to analyze the match between the physics agenda and the experimental capabilities planned for the upgraded facility.

The Charge made to PAC XXIII by the Laboratory management is given in Appendix B. It requests a review of the content, impact, and the formulation of the scientific case being developed in the context of an upgraded experimental facility with new capabilities and much greater technical reach than has heretofore been possible.

The PAC held an extended meeting on January 17-22, 2003 with an enlarged membership to respond to this charge. The agenda (Appendix C) included extended discussions with the JLab User community, the Hall leaders, and the Laboratory management. The Committee (Appendix D) then held several days of review and discussion of the scope of the science program, its impact, and the accelerator capability and instrumentation needed to address the physics opportunity.

An analysis of the current physics program at JLab in relation to the proposed program and an overview of the proposed facility upgrade, are discussed in Sections II and III of this Report. An overview of the PAC assessment of the physics driving the upgrade is given in Section IV. The major elements of the new science program, as envisioned by the PAC, are presented in a topic-by-topic evaluation in Section V. In Section VI, the science driving the upgrade is matched against the technical reach of the proposed new experimental facility. The findings of this review, as established by the Committee, are formulated in four recommendations to the JLab management and are presented in Section VII, followed by a brief summary in Section VIII.

JLab Proposed Program:

II. Context and New Physics Thrusts for the JLab 12 GeV Research Program

The scientific program at Jefferson Lab is now producing a wealth of new results and starting to reveal the discovery potential of this successful facility. The most striking examples include the demonstration that the proton charge and magnetic form factors exhibit markedly different behaviors at high momentum transfers; the first exclusive measurements of Deeply Virtual Compton Scattering, strongly suggestive of the manifestation of scattering at the quark level; high energy deuteron photodisintegration, illustrating for the first time the scales at which the meson-baryon description of a nucleus appears to be breaking down; and new insights into parton distributions at large values of the Bjorken variable x, in particular through experimental tests of the concept of duality. These successes, as well as other important results combined with the development of new theoretical concepts, are opening up new frontiers that require higher energy to exploit the exciting physics opportunities.

The most striking new theoretical concept is that of the recently developed Generalized Parton Distributions. Within the well defined framework of Quantum Chromodynamics, the Generalized Parton Distributions provide a unifying description of the quark structure of the nucleon. In addition, continuously improving lattice QCD calculations will be matched by new experimental results in meson and baryon structure to be obtained at JLab.

In this context, the Jefferson Lab User community and the Laboratory have identified key research areas for the future. Among these, the PAC, in accordance with previous reviews, recognizes two large programs as providing exceptional opportunities:

- -The discovery and characterization of the role of glue in the excitation of mesons would unravel the nature of quark confinement. Theoretical developments indicate that hybrid quark-gluon or purely gluonic configurations should exist in the meson sector, and the expectation is that they are in a mass region uniquely accessible with an 8-10 GeV polarized photon beam.
- -The quark structure of the nucleon will be explored in, up to now, inaccessible regions and dimensions, extending the present measurements of parton distribution functions and leading to new partonic distributions. In particular, Generalized Parton Distributions would be extracted from a variety of deeply virtual and exclusive reactions measured with great precision up to the highest momentum transfers.

These and other important research domains are examined in this report. They lead the User community and the Laboratory to propose a significant upgrade of the CEBAF accelerator to a beam energy of 12 GeV, together with the construction of new detectors and a new Hall. Beam energy, polarization, luminosity, acceptance, and precision are crucial for these new physics thrusts.

III. Overview of the Proposed Facility Upgrade

The proposed facility upgrade evaluated in this document is the product of a series of workshops and reports (see Appendix A) generated by the users and the staff of the Thomas Jefferson National Accelerator Facility. It is primarily driven by the next generation science program envisioned at JLab. The proposed upgrade is briefly summarized here. A detailed discussion of the new experimental equipment as it relates to and is driven by the physics program together with a PAC assessment, is given in Section VI.

Accelerator

The maximum energy of the North and South Linacs will be raised from 0.6 GeV to 1.1 GeV by increasing the number of superconducting r.f. cavities and by taking advantage of their increased performance, including their higher gradients. By also increasing the bending power in the recirculation arcs, electron beams with energies up to 11 GeV will be available for experiments in the existing halls A, B and C. By adding another arc at the end of the South linac the beam can be recirculated again through the North linac, yielding a beam with a maximum energy of 12 GeV for a new Hall D.

To utilize the increased maximum electron energy effectively, the experimental equipment in the existing halls will be upgraded. The planned additions comprise the following apparatus.

Hall A

In Hall A a new magnetic spectrometer, MAD (Medium Acceptance Device), will be constructed. It combines good energy resolution with medium solid angle and large momentum acceptance. This spectrometer will be used as the electron detector for inclusive (e, e′) measurements, and in combination with one of the existing HRS spectrometers or a calorimeter, for the detection of the produced hadrons in (e, e′h) experiments. The solid angle of MAD will be especially important for the measurement of very small cross sections, which occur, e.g., at large x and/or Q^2.

Hall B

In Hall B the present toroidal detector CLAS (CEBAF Large Acceptance Spectrometer) will be reconfigured and moved to a more forward angle. This will give much better forward-angle coverage and better particle identification. The forward-angle detector will be complemented by a central detector consisting of a solenoid plus a detector system for charged and neutral reaction products up to 135°. The hermeticity of the detector will be greatly improved, thus providing much cleaner identification of exclusive final states. The new CLAS++ detector would operate at luminosities up to 10^{35} $cm^{-2}s^{-1}$, a factor of ten higher than the present detector. It will be especially suitable for studying reactions with multi-particle, including photon and neutron, final states.

Hall C

In Hall C a new magnetic spectrometer, SHMS (Super High Momentum Spectrometer), will be constructed. It will enable the detection of reaction products with the highest momenta that can be produced with an 11 GeV electron beam. Furthermore it will be able to reach scattering angles as low as 5 degrees. It will have good momentum and angle resolution and large momentum acceptance, but relatively small solid angle. The SHMS will be used, often in combination with the existing High Momentum Spectrometer (HMS), for precise L/T separations, especially at high Q^2, and for the study of (semi-) exclusive reactions at high values of z, where a reaction product has a large momentum or is emitted at a small angle.

Hall D

The 12 GeV electron beam will be used to produce the linearly-polarized photons needed for the exotic meson physics program. Coherent bremsstrahlung and tagging will be utilized to produce a 9 GeV photon beam with high intensity (10^8/s) and 40% linear polarization. The photon beam will be directed to a new experimental hall, Hall D, equipped with a dedicated 4π detector, consisting of a large aperture superconducting solenoid with tracking chambers, a Cherenkov detector, and a calorimeter. The hermetic 4π design and detector layout ensure that virtually all the meson decay products can be identified.

Other equipment

A general-purpose large-acceptance calorimeter is planned for use in Halls A and C. It will be used for a number of high-Q^2 exclusive reactions. Polarized targets, high-power targets and high-precision beam polarimeters are also an essential part of the program.

PAC Assessment:

IV. Overview of the Science Impact of a 12 GeV Physics Program

The PAC reviewed all the research areas identified in the preliminary Conceptual Design Reports and developed by several User Working Groups as the major thrusts for a 12 GeV upgrade. This section gives a short overview of the major components of that physics program and identifies what in the PACs view are the major drivers for the Upgrade. A full topic-by-topic evaluation of the research areas that would be enabled by the JLab 12 GeV Upgrade is provided in Section V.

IV. A. The role of glue in meson excitations and the origin of quark confinement

The dynamics of quarks and gluons leading to the phenomenon of confinement are among the outstanding unsolved problems in physics. Theory and computation in lattice QCD have led to the concept of quarks interacting through the development of flux tubes. These flux tubes contain the gluonic degrees-of-freedom, which can be excited to generate "hybrid" states. Lattice calculations also point to the existence of "glueballs", states solely composed of gluons. These new states, collectively known as gluonic excitations, represent the only case of a theory in which the guage particles are also constituents.

Whereas a few experimental indications for the gluonic excitation of mesonic states have been reported, Jefferson Lab, with the proposed 12 GeV upgrade, would be in a unique position to search systematically for such states and to determine their properties. The case for the use of a polarized photon beam to create these states is well argued. The 12 GeV upgrade would provide both the kinematical reach and statistics combined with a level of precision, hitherto unavailable. The combination of the intense polarized photon beam and the hermetic detector provide a unique and powerful opportunity to explore this physics.

The PAC cautions against the exclusive use of the flux tube concept as the intellectual framework. The existence of hybrids is not predicated upon the flux-tube formulation of the interaction: the mere existence of gluons and their self-interaction is sufficient. Strengthened efforts in lattice QCD computation in the light-quark sector will be an asset for this program.

The PAC is very enthusiastic about the fundamental character of this physics and the discovery potential of this project.

IV. B. A unified determination of the quark (and gluon) structure of the nucleon

A comprehensive program of measurements concerning nucleon structure emerges as a major initiative in the upgrade proposal. Recent theoretical advances have established, within the framework of QCD, the concept of Generalized Parton Distributions (GPD), which are accessible through deeply virtual exclusive reactions. These GPDs contain the correlations between quark-states of different momenta within the nucleon, and thus reach beyond the “ordinary” parton distributions. They provide, among other properties, a simultaneous determination of the longitudinal momenta of quarks and of their transverse position within the nucleon. For the first time a three-dimensional picture of the proton and neutron could thus be built from measurements. This construction links the “ordinary” parton distributions and elastic form factors. It also promises to unravel long-standing puzzles related to determining the contribution of the quark orbital angular momentum to the spin of the nucleon.

Theoretical work in this domain is flourishing, thus strengthening the case for an intense well focused program aimed at the experimental determination of these GPDs. Exclusive reactions, deeply virtual Compton scattering and meson production, could be measured with unprecedented precision and kinematical range with the proposed 12 GeV upgrade.

In parallel with this new initiative, the JLab 12 GeV upgrade provides the luminosity and kinematical reach to make much improved determinations of the nucleon parton distribution functions (PDFs) at moderate to large x. The spin and flavor structure will be separated with unprecedented accuracy. The universal nature of the PDFs makes them of great interest to a broad community. Other revealing one-dimensional parton distributions, such as transversity distributions, will be mapped out as well using semi-inclusive deep inelastic scattering.

To complete this program, measurements of the pion form factor and the nucleon elastic and transition form factors will be extended to the highest possible momentum transfers. These form factors provide a fundamental characterization of the hadron structure.

The PAC is also very enthusiastic about this program and the potential it has for developing a deeper understanding of the underlying structure of the nucleon.

As additional topics, the PAC recognizes that 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 PDFs, in other areas of particle and nuclear physics should be investigated and illustrated.

IV. C. Two Research Domains Requiring Further Development

A number of other research opportunities are presented in the pCDR and are reviewed in Section V of this report. Most of them fall in two categories, which are emphasized in the final recommendations (Section VII). The first comprises a number of revealing phenomena to be studied in nuclei (see Section V.C). The second concerns tests of the Standard Model of interactions and determination of the fundamental parameters of this model (Section V.D). Both topics require a facility upgrade to 12 GeV and the latter requires instrumentation not included in the base equipment plan.

The PAC considers both these research programs, (see Sections V.C and V.D), as fundamental and having the potential for high scientific impact. They would substantially enrich the scope of research activity at the new facility. These programs could be more fully developed, in one case towards a more comprehensive framework, and in the other case for experimental feasibility. Furthermore, connections between these and on-going research in the fields of ultra-relativistic heavy-ion collisions, nuclear structure, and particle physics should be made more explicit.

V. Elements of the Science Program Driving the Upgrade

After a careful analysis of the science opportunities enabled by a 12 GeV Upgrade of JLab, the PAC concluded that the major drivers for the Physics program are those outlined in Section IV. The PAC's view on the scope and impact of the individual science topics that are the underpinnings of this analysis is discussed in detail in this section.

V. A. MESON DYNAMICS

Introduction

Strongly interacting matter is described by quantum chromodynamics (QCD), the non-Abelian field theory in which quarks interact through a color force carried by gluons. The quarks and gluons do not appear as free fields in isolation; this is the phenomenon of "confinement", which is unique in science. Mesons are the simplest system for studying strong (non-perturbative) QCD, providing the unique possibility of exploring the interaction of non-Abelian fields in the strong interaction limit. Photon beams, with J=1 and mixed I=0,1, can be used to produce a rich spectrum of mesons with a variety of spins and flavors. With a 12 GeV electron beam the threshold above which the origins of confinement can be investigated will be crossed, as it is at such energies that the non-Abelian fields are expected to be excited in strong QCD. Due to confinement, quarks and gluons do not exist as free particles and only color-singlet combinations are allowed. In addition to the well-studied color-singlet combinations $q\overline{q}$ (mesons) and qqq (baryons), others are possible in which gluonic degrees-of-freedom are excited, either in isolation ("glueballs") or in the presence of $q\overline{q}$ ("hybrids"). These new states, collectively known as gluonic excitations, are fascinating since QCD is the only theory in which the gauge particles are also constituents.

In lattice QCD calculations for the $q\overline{q}$ meson system, the field lines associated with the color force between the quark and the antiquark are compressed into a narrow tube, a flux tube, by the self-interaction of the gluons. Within this picture, conventional $q\overline{q}$ mesons result when the flux tube is in its ground state. Excitations of the flux tube then lead to hybrid mesons that exhibit both quark and gluonic degrees of freedom. However the flux-tube concept is not essential for the existence of hybrids and glueballs. The presence of gluons and their self-interaction is sufficient. Hybrids and glueballs are also predicted to exist (with somewhat different masses and properties) in constituent gluon models and in bag models. The idea that gluonic excitations must exist is very general. Indeed, one may reverse the argument; if gluonic excitations do not exist then QCD is incorrect.

Most studies of mesons have been limited by kinematical reach or by statistics or both. It is for these reasons that little is known about $q\overline{q}$ mesons above 1.8 GeV/c^2; there is evidence only for the lightest glueball and that hybrids, which have a small signal, are only now beginning to be observed. This will change completely with the 12 GeV upgrade, which will have the kinematical reach, up to masses of 2.5 GeV/c^2, and the necessary statistical accuracy. This will be an extensive program, starting with the exotic hybrids, identified by their unique quantum numbers. The intention is to investigate the pattern of the hybrid nonets and their interaction, via mixing, with the $q\bar{q}$ nonets. As the lighter glueballs will also mix with the $q\bar{q}$ mesons it is axiomatic that glueball studies can be made as well. There are considerable advantages in using a photon beam. The spin of the photon and its combined isoscalar and isovector nature lead to a wider spectrum of final states than is possible with a pion beam. Further, the ability to polarize the beam provides information on the production mechanism, greatly aiding the analysis.

Light-quark $q\bar{q}$ *Systems*

The light-quark mesons are grouped in families of nine members, nonets, characterized by specific J^{PC} quantum numbers determined by the relative spin of the two quarks and their relative orbital angular momentum. Radial and orbital excitations of the quarks are allowed. The average mass of the lowest nonets is about 0.8 GeV/c^2 and each radial or orbital excitation adds of the order of a further 0.5 GeV/c^2. Most expected nonets up to a mass of about 1.8 GeV/c^2 are well established, but above that, only a limited number of states have been identified. A good example of missing states occurs with $s\bar{s}$ strangeonium where only five states have been identified. The $s\bar{s}$ states are important as they are a bridge between the light u,d quarks and the heavy c,b quarks. Photo-production is an excellent technique for producing $s\bar{s}$ mesons as, in effect, the incident beam is a vector-meson beam with a large ϕ component. Sometimes the s-quark behaves like a light quark as part of an $SU(3)_{light}$ multiplet and sometimes as a heavy quark as part of an $SU(3)_{heavy}$ multiplet. The vector $s\bar{s}$ states can be studied in e^+e^- annihilation at Novosibirsk and as well through initial state radiation (ISR) at BABAR and Belle. The photoproduction experiments discussed here are complementary to the annihilation studies, since these two reactions are sensitive to different aspects of the meson wave function. Unexplained differences already show up in existing data. For example, the $\phi(1680)$ is apparently seen in both K- $\bar{\text{K}}$ and K-K* channels in e^+e^- annihilation, but there is no corresponding K-K* signal in the photoproduction measurements.

Hybrid $q\bar{q}$-g

The excitation energy of the first excited state of the flux tube is expected to be about 1.0 GeV so one anticipates that the lightest hybrids will have a mass of about 1.8 GeV/c^2. A particular feature of the hybrids is that J^{PC} quantum numbers are allowed which are forbidden in the conventional quark sector. Specifically these quantum numbers are $J^{PC} = 0^{+-}$, 1^{-+} and 2^{+-}. They are referred to as “exotic” and their signature is unique. Experimental observation of states with exotic $J^{PC}=1^{-+}$ quantum numbers have been reported, by the Brookhaven E852 collaboration and by the CERN Crystal Barrel collaboration, with a mass of about 1.4 GeV/c^2 and by the E852 and the Serpukhov VES collaborations with a mass of about 1.6 GeV/c^2. Like the conventional mesons, the hybrids form nonets so the exotic states are only the tip of a large iceberg. A small piece of the iceberg may have appeared in the 4 pion channel in e^+e^- annihilation. The cross section is large, but the standard model of meson decay excludes this for $J^{PC} = 1^{--}$ $q\bar{q}$ states. Since a $J^{PC} = 1^{--}$ hybrid is expected to decay almost exclusively to 4 pions, an explanation of the large 4 pion cross section is that it is due to a vector hybrid. States with $J^{PC} = 1^{--}$ will be produced copiously in photoproduction.

Glueballs

Lattice QCD calculations indicate that the lowest-mass glueball, a state of pure glue, should have $J^{PC} = 0^{++}$ and a mass of about 1.5 GeV/c^2. Experimentally there are three scalar states in this mass region while only two are expected on the basis of the $q\bar{q}$ meson nonets. The inference is that the scalar glueball is mixed with two of the $q\bar{q}$ states. There is an indication of a tensor glueball, $J^{PC} = 2^{++}$, at about 2.0 GeV/c^2, but this requires confirmation. The exotic analogues of the hybrid mesons are not expected below 3.0 GeV/c^2. Radiative decay of the J/ψ is expected to be a copious source of glueballs and studying this will be part of the CLEO-C program. However the relative strengths of the physical states starting with a purely gluonic system will differ from those obtained from a purely $q\bar{q}$ system. Comparing and contrasting the two adds to the interpretation of the dynamics.

Radiative Decays

The decay dynamics of $q\bar{q}$ mesons, hybrids and glueballs with the same quantum numbers will generally differ. In a hybrid meson the $q\bar{q}$ pair is in a different spin-parity state than that in a $q\bar{q}$ meson with the same overall quantum numbers as the hybrid. The decay of a glueball is “democratic” as it couples equally to u-ubar, d-dbar and s-sbar states. So in principle, the hadronic decay modes are an important signal that gives an insight into the internal dynamics. An even better probe of the internal structure is provided by radiative decays for which the model dependence is less and the sensitivity greater. They are an excellent flavor filter. Until now relatively few radiative decays have been determined. The 12 GeV upgrade with its high luminosity will change this, and will allow the first detailed studies of meson radiative decays.

Partial Wave Analysis

To identify the J^{PC} quantum numbers of a meson it is necessary to perform a partial wave analysis (PWA) of multi-meson systems. While the implementation of a PWA is in principle straightforward there are both empirical and intrinsic difficulties. These can be minimized by careful experimental design and high statistics. Even so the PWA is subject to mathematical ambiguities for certain final states because two or more different amplitudes may lead to identical final states. This difficulty can be handled by assuming some a priori physics knowledge or, preferably, by studying simultaneously several final states. This latter information is required in any event as it is critical in understanding the underlying dynamics of the mesons and their interactions. 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. PWA requires that the entire event be kinematically identified. All particles should be detected and measured, and there should be sensitivity to a wide variety of decay channels. The detector should be hermetic for neutral and charged particles with excellent resolution, uniform acceptance and particle identification capability. The proposed development of Hall D satisfies all of these criteria.

In photoproduction on a hydrogen target there is a background to the meson states coming from the production and decay of baryon resonances. One way in which this can be eliminated is to use coherent photoproduction on a ^{4}He target, while detecting the ^{4}He recoil. A disadvantage of this procedure is that only neutral meson states can be accessed, although as the photon is a combined isoscalar and isovector state both isoscalar and isovector mesons can be produced. There may be advantages in charge-exchange processes. A possible way to achieve this and still avoid the baryon-resonance background is to use a ^{3}He target and to detect the recoiling ^{3}H. While an intense electron beam combined with a ^{3}He gas target would be an ideal setup with high luminosity, a solution involving a small diameter high-pressure gas target in a tagged photon beam may also be viable.

The Pion

The pion is not only the lightest meson (having one-fifth the mass of the rho meson), it is in some ways the most enigmatic. It is fair to ask: what is a pion? This can best be answered by combining data for the charged pion form factor with data for the neutral pion transition form factor. At low Q^2 the full non-perturbative structure is accessed. At higher Q^2, the reaction mechanism is possibly best described as the “handbag” mechanism, with the relevant non-perturbative structure encoded by the generalized parton distributions (GPDs). It is widely believed that at higher Q^2 the GPDs evolve to the asymptotic limit of perturbative QCD. Any acceptable theory has ultimately to understand how this evolution occurs. Understanding the transition from strong to perturbative QCD is an important goal and it is expected that the pion will show this transition at much lower values of Q^2 than the nucleon. A related measurement of the ratio of π^+/π^- cross sections will also provide essential information.

SUMMARY

Photoproduction at 12 GeV enables measurements above the threshold at which the gluonic degrees-of-freedom in strong QCD are predicted to exhibit collective excitation, whereby the origins of quark confinement can be investigated. It represents a wide-ranging program requiring a dedicated facility. Elucidating the nature and dynamics of mesons with masses in the 1.0 to 3.0 GeV range is important also for the analysis of B decays and for the dynamics of charmed mesons.

V.B. The Structure of the Nucleon and Other Baryons

V.B.1. Large-x Flavor and Spin Structure of Nucleons

As one of the fundamental sets of observables in strong interactions, the parton distribution functions (PDFs) of the nucleons have been extensively studied in recent decades. Major surprises concerning the spin and flavor structure of the PDFs were found, including the spin composition of the nucleon and the flavor asymmetry of the light nucleon sea. On the theoretical front, advances in Lattice QCD calculations lead to precise predictions of the moments of the PDFs, which are ready to be compared with experiments. The universal nature of the PDFs makes them of great importance to a broad community.

Large x region

The JLab 12 GeV upgrade offers a unique opportunity to determine the flavor and spin structure of the nucleon PDFs in the moderate to large-x regime with unprecedented precision. Access to the high-x frontier is made possible through the combination of luminosity and kinematic range that satisfies the traditional Deep-Inelastic Scattering (DIS) criteria (W>2 GeV, Q^2>1 $(GeV/c)^2$). The 100% duty factor, high luminosity and beam polarization of JLab, combined with the availability of highly polarized targets, are essential ingredients in the successful determination of PDFs for x > 0.3. Moreover, recent progress in understanding the role of parton-hadron duality in the nucleon PDFs, may allow the x-range to be extended to x values as high as 0.95.

To study various aspects of the large-x physics, inclusive and semi-inclusive scattering of polarized electrons off targets of unpolarized and polarized hydrogen, deuterium and ^{3}He will be performed. Separations of the longitudinal and transverse responses are needed. Flavor decomposition can be made via a comparison between the proton and neutron data, and via the method of flavor tagging in Semi-Inclusive DIS (SIDIS). The behavior of u(x), d(x), Δu(x), Δd(x), $A_1^p(x)$, and $A_1^n(x)$ as x approaches 1 can be accurately determined and compared with predictions of various approaches to modeling the strong interaction problem. These data will also have major impacts on mapping out the x-dependence of the PDFs, which are essential inputs for calculating all hard processes in high-energy hadron collisions.

Duality

There has been significant progress recently in the theoretical understanding of "Duality", the phenomenon in which structure functions measured at low W (and Q^2), when averaged over an appropriate energy range, follow the scaling given by a simple quark-gluon theory. To obtain a deeper understanding of the physics underlying duality, studies with different flavor and spin filters (including L/T separations) are needed with the much wider range of kinematics accessible with 11 GeV electrons. For structure functions where the accessible Q^2 range demonstrates that duality is valid, PDFs can be extracted at higher x than is possible if traditional DIS limits on W and Q^2 are imposed. Duality studies are also crucial in establishing kinematic regions where independent target and current fragmentation can be applied in the interpretation of SIDIS.

Semi-Inclusive Reactions
By studying azimuthal angle dependences in semi-inclusive reactions on polarized targets one has access to an extended set of responses. Given factorization, these can be characterized by orders of twist and chirality (transversity, Sivers function, Collins function, etc.). Determination of the dependences on detected hadron and spin azimuthal angles, is required to isolate the various responses and hence the extended set of parton distributions. Some of the latter are sensitive to the quark orbital angular momentum; others may help to shed light on initial and final state partonic interactions.

GDH Integral
Improved measurements of the spin structure function, g_1 , at higher energies over a broad range of Q^2 , will improve the determination of the extended GDH integral for both the proton and neutron. The low Q^2 results will allow more stringent tests of chiral perturbation theory calculations.

The proposed program for large-x physics is rich, comprehensive, and technically feasible. This includes studies with neutrons as well as protons. The former is based on experimental techniques that have either been demonstrated in recent experiments (where a polarized ^{3}He target was used) or are being actively developed (such as neutron tagging). Measurements of this type, benefit from having transversely as well as longitudinally polarized targets.

Some areas have been identified where the physics case might be broadened and strengthened:

- -It might be possible to extract new information on gluon distribution functions, G(x), and especially the poorly known polarized gluon distribution, $\Delta G(x)$, at large x via an analysis of the Q^2-dependence of the $F_2(x)$ and $g_1(x)$ structure functions.
- -The proposed method of SIDIS for measuring Δu and Δd, in which one looks at the flavor of the leading hadron in the final state, could be supplemented with the method based on the analysis of $g_1^p(x)$ and $g_1^n(x)$ obtained in inclusive DIS.
- -It would be useful to show explicitly the uncertainties of u(x), d(x), $\Delta u(x)$, $\Delta d(x)$ from recent global analyses of unpolarized and polarized PDFs and compare them with the expected statistical accuracies at 11 GeV. It is likely that significant improvements will be made even to the unpolarized up quark distribution, which is presently not well-known.
- -Two methods have been proposed to extract the d/u ratios. An independent check would be to use flavor tagging in SIDIS on a hydrogen target.
- -The proposed measurements of the Q^2 dependence of the ratio of longitudinal to transverse structure functions, R, will be highly sensitive

to gluons, and can provide another means for probing the gluon distributions in the nucleon.

In summary, the 12 GeV upgrade at JLab provides the energy, duty cycle, and luminosity needed to make vastly improved determinations of the flavor and spin dependent valence quark distributions in the nucleon. Through comparison with lattice QCD calculations of moments, powerful tests of the underlying theory can be made. The universal nature of the PDFs makes them of interest to a broad spectrum of nuclear and particle physics endeavors.

V.B. 2. Generalized Parton Distributions from Deeply Exclusive Reactions

Much of the currently available information on the structure of the nucleon has come from inclusive electron scattering. Measurements of elastic form factors have been used to deduce the transverse size of the proton while forward parton densities from deep inelastic scattering have provided longitudinal projections of the nucleon's momentum and spin distributions. As revealing as these glimpses have been, they are but two orthogonal slices through the full parameter space that characterizes the dynamical structure of the nucleon. A new initiative is under way at Jefferson Lab to reconstruct the nucleon's full internal dynamics. This is much more complex than the two studies mentioned above, but its ultimate goal is nothing less than the development of tomographic-like images of quark densities of varying spin, flavor, and momentum.

The framework for the new initiative is a recently developed formalism that describes the nucleon's quark-gluon substructure in terms of four Generalized Parton Distributions (GPDs). The formalism takes advantage of QCD-based factorization theorems to relate these GPDs to observables in deeply exclusive reactions described by a handbag-like process. In this process, a quark with a given longitudinal and transverse momentum fraction is removed from the initial state nucleon and reinserted into the final state nucleon with a different momentum fraction. The GPDs are functions of three kinematic variables: x, the average longitudinal momentum fractions of the quark in the initial and final states; ξ, the difference between these quantities; and t, the momentum transferred to the nucleon. The quark distributions of longitudinal momenta measured in deep inelastic scattering are just GPDs at the forward limit of $\xi = t = 0$. Elastic and transition electron scattering form factors are ξ-independent x^{o}-moments of GPDs, depending only on t and measuring transverse size. Similarly, the t-dependent form factors in real Compton scattering (RCS) are ξ-independent x^{-1}-moments of GPDs. The full GPD parameter space connects transverse and longitudinal information, including their correlations. The GPDs are independent of the specific reaction channel used to probe the nucleon, thus providing a unifying framework encompassing all channels.

Unfolding the GPDs requires exclusive reaction data, specifically Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP). The latter falls off as $1/Q^6$, while DVCS drops only as $1/Q^4$ and so dominates at high Q^2. DVCS also has fewer higher-twist corrections and so is generally regarded as the cleanest access to the underlying GPDs. For given values of ξ and t, DVCS cross sections give information on the GPDs integrated over x, while spin asymmetries access points at $x = \pm\xi$. However, virtual Compton scattering is always in competition with the Bethe-Heitler (BH) process. On the one hand, this is advantageous since the DVCS-BH interference allows access to the imaginary part of the DVSC amplitude and provides valuable information on large regions of the GPD parameter space. But at the current JLab energy of 6 GeV it also presents an experimental challenge for extracting DVCS amplitudes in the presence of BH components that are an order of magnitude larger. However, at 11 GeV DVCS is comparable to BH, which greatly improves the sensitivity to both DVCS and the DVCS-BH interference. Asymmetries in Deeply Double Virtual Compton Scattering (DDVCS) reactions, such as $ep \rightarrow epe^+e^-$, though experimentally much more challenging, are not constrained to $x = \pm\xi$, and thus could potentially map out the full space between these limits.

The longitudinal part of DVMP cross sections is also expected to be dominated by handbag-like diagrams and comparisons between vector and pseudoscalar channels can be used to separate the contributions from two different classes of GPDs. This requires either a traditional L/T separation combining measurements at different energies, or a measurement of the polarization of the produced vector mesons.

Ultimately, unfolding of the underlying GPDs for each flavor requires a comprehensive set of data on cross sections, beam asymmetries, and longitudinal as well as transverse target asymmetries, for both DVCS and DVMP reactions on polarized targets, measured over a large kinematic range in Q^2, x, and t. This represents a substantial Laboratory program. The success of this initiative relies critically on the following:

- a doubling of the present electron energy, to reach the regime where DVCS becomes large, and handbag-like amplitudes begin to dominate. Here higher-twist corrections are small;
- detector upgrades, MAD and a calorimeter in Hall A and CLAS++ in Hall B, to completely determine the final states in exclusive reactions with the required energy resolution, and the SHMS in Hall C for high Q^2 L/T separations;
- a high product of luminosity and acceptance to compensate for the rapidly falling exclusive cross sections at high Q^2;
- polarized electron beams and polarized targets to test for higher-twist contributions and to unambiguously access specific components of GPDs;
- large acceptance capability to measure multi-particle final states resulting from the production of different vector mesons in DVMP.

In addition, the PAC notes the following:

- While DVMP from the proton has sensitivity to the flavor decomposition of GPDs, experiments on a quasi-free neutron target could also access similar (though possibly distinct) information. At present, no DVCS or DVMP experiments on the neutron have been proposed. The feasibility of such measurements would be worth investigating.

- Form factor measurements, both for elastic electron scattering and RCS, as discussed in the next section, are also proposed and would probe the GPDs at the highest t values.

- A large range of DVCS, DVMP, DDVCS experiments together with data on ordinary parton distributions, elastic and resonance form factors, and RCS experiments will potentially impact our knowledge of the underlying GPDs. However, the precision required to unfold the GPDs from these data has not yet been identified. An effort should be mounted to address this question with the aim of optimizing the overall program.

Related experiments are planned or underway at COMPASS and HERMES, although their reach is limited to about $x < 0.3$ and $Q^2 < 6$ (GeV/c)^2 , whereas the planned JLab program will extend well out to the valence region, up to $x = 0.76$ and $Q^2 = 10$ (GeV/c)^2 and with much higher luminosity and hence statistics. The JLab effort is unique in its coverage of kinematics (with high statistics), scope of reaction channels and polarization observables. The wealth of experimental data taken together, involving information from other laboratories where available, will give completely new insights into nucleon dynamics and quark correlations, ultimately providing strong constraints for the modeling of tomographic images of the proton and neutron.

V.B. 3. Form Factors

Form factor measurements have been an important component in our study of the electromagnetic structure of nucleons and nuclei for almost five decades. These classic studies have yielded precise information on the detailed distribution of charge and magnetization in protons, neutrons, and complex nuclei. The exploitation of spin observables, intense polarized beams, polarized targets, and recoil polarimetry during the past decade has opened an important new window on their basic distributions. One can now accurately extract small electromagnetic amplitudes via their interference with the dominant terms. Baryonic form factors are discussed here, and nuclear form factors are discussed in section V.C.

Elastic Form Factors
Understanding the structure of the nucleon involves probing the shortest distance scales between quarks and therefore requires data at the highest possible Q^2. JLab at 12 GeV allows for an extension of the presently available Q^2 range by factors of two to four in many cases.

In a modern approach, elastic form factor can be thought of as zeroth-order moments of GPDs. Thus form factors are the only way to access GPDs at large t. Such data would provide crucial information on the nucleon wave function and ultimately may enable the development of a three-dimensional description of the nucleon.

It is important to extend the measurement of the four nucleon form factors (G_E^p, G_M^p, G_E^n, G_M^n) to the highest possible Q^2 and precision. An important theoretical goal would be a unified model description of the nucleon, which incorporates these four nucleon form factors. The magnetic form factor of the proton, G_M^p, is the only one that has been measured for Q^2 greater than 6 $(GeV/c)^2$ with relatively good accuracy. Using spin observables, G_E^p/G_M^p has been measured up to $Q^2 = 6$ $(GeV/c)^2$. The measured ratio falls quite rapidly as a function of Q^2, at variance with the assumptions about the proportionality of G_E^p and G_M^p. There is great interest in the behavior of this ratio for even higher Q^2 ; at 12 GeV the Q^2 range would be extended to 14 $(GeV/c)^2$. Knowledge of neutron form factors at high Q^2 is equally important. For the neutron, G_M^n would be extended up to about 10 $(GeV/c)^2$. Similarly the maximum Q^2 for G_E^n would be increased well beyond the current range of 1.5 $(GeV/c)^2$ up to 5 $(GeV/c)^2$. At such momentum transfers, the influence of the pion cloud is likely to be very small so that the effects of relativistic quarks will be studied.

Real Compton Scattering (RCS)
Investigation of RCS at high Q^2 and wide angles involves the measurement of cross sections and longitudinal and transverse polarizations. In the GPD picture the observables involve the x^{-1} moments. The recent JLab data have been interpreted in this framework. The large $-t$ behavior of the GPDs and therefore the transverse distribution of quarks at small impact parameters in the nucleon would be significantly constrained by extended RCS measurements. At 12 GeV it would be possible to extend $-t$ and s up to 20 $(GeV/c)^2$. The RCS form factors R_V, R_T, and R_A are expected to scale with -t and s according to pQCD. The higher Q^2 data could provide important information on this transition to pQCD.

Resonance transition form factors
Measurements of resonance transition form factors access additional GPD components that are not directly probed by elastic scattering or Real Compton Scattering. The $N \rightarrow \Delta$ form factors are connected to the isovector components of the GPDs. At 12 GeV the dominant $N \rightarrow \Delta$ form factor would be extended to almost 18 $(GeV/c)^2$. Similarly the multipole ratio E_{1+}/M_{1+} which naively is related to the quadruple deformation of the nucleon and the Δ would be extended up to

about 12 $(GeV/c)^2$. One might see the ratio depart from its current near zero value to approach the pQCD prediction that $E_{1+}/M_{1+} \sim 1$ in this Q^2 range.

The transition to $S_{11}(1535)$ will also be studied. The S_{11} amplitude is expected to scale with Q^3. However the current data to $Q^2 = 4$ $(GeV/c)^2$ do not yet show the expected scaling behavior. The upgraded facility would allow extensions of the data up to about 20 $(GeV/c)^2$.

V.C. Parton-Hadron Structure of the Nucleus

High Density Cold Nuclear Matter

Jefferson Lab at 12 GeV would be unique in its ability to observe nuclear reactions with very high values of Q^2 and x, excellent resolution, and reasonably high counting rates. These assets represent a unique tool for studying several apparently diverse subjects related to high-density nuclear configurations that are an essential feature of nuclear ground states. For example, ab-initio nucleon-based calculations originating from effective field theory predict that there are brief time internals when two or more nucleons overlap in space. Such configurations are important in understanding the structure of even more dense objects such as neutron stars, or even quark stars, The suggested experiments at 12 GeV, along with the present program, are expected to test the validity of, and eventually determine, the limits of the nucleon-based conception of the nucleus.

Short Range Correlations

Measurements of quasi-elastic electro-disintegration of light nuclei at $1.5 < Q^2 < 4$ (GeV/c)^2 , covering a wide range of angles and missing momenta (in excess of 1 GeV/c) can provide a detailed look at short range correlations. Deep-inelastic electron-nuclear-scattering can be studied at values of x that are much greater than one, to determine, in a model-independent way, the probability of finding a quark that carries a larger light-cone momentum than one would expect from a quark in a low momentum nucleon. Studies of tagged structure functions (measurement of a nucleon from the target fragmentation region in coincidence with the outgoing electron) can be used to directly observe the presence of non-nucleonic degrees of freedom in droplets of high-density matter. The form factors of few nucleon systems can also be studied with unprecedented experimental and theoretical precision.

One way to summarize the goal of these diverse studies is that ultimately each is aimed at answering the question: do the normal color singlet configurations continue to dominate? Determining the nature of high-density cold nuclear matter will answer this and other questions.

High Momentum Transfer and High Energy Reactions

The use of high momentum transfer reactions, enabled by the upgrade, will allow the color singlet nature of strongly interacting matter to be illuminated. For example the domination of color singlet configurations can be examined with studies of the $\gamma + \mathrm{d} \rightarrow$ □+□ reaction.

There are other techniques. Color transparency is the study of color-singlet point-like configurations, PLC, formed in coherent high Q^2 reactions, which do not undergo initial or final state interactions. Strong evidence for a pionic PLC has been observed in a FermiLab experiment. High resolution experiments at JLab could allow a nucleonic PLC to be discovered and studied, thereby confirming one of the implications of the SU(3) nature of color.

Studies of nuclear hadronization processes employ the nucleus as a tool. The basic idea is to strike a quark in the nucleus (by knocking it out of a nucleon) and to observe how it propagates. These processes are studied with theories also used to analyze RHIC experiments; the measurements driven by an electromagnetic probe would provide a base or baseline in analyzing high energy heavy ion collisions.

V.C.1. Probing the limits of the nucleon-based description of nuclei

A fundamental issue in our understanding of nuclear physics is to determine at which length scale the description of nuclear properties in terms of meson-baryon based interactions must be replaced by descriptions that use quark and gluon degrees of freedom. With the proposed 12 GeV upgrade, a kinematical region becomes accessible where a few selective experiments on nuclear targets can be performed. These will probe that part of the nuclear response where nucleons are in such close proximity that they may change their internal structure or even may fuse into six quark clusters. Aspects of these high-density configurations are described by the poorly known short-range part of the NN-interaction, normally defined in terms of heavy-meson exchange.

Elastic form factors of the few-body nuclei ^{2}H, ^{3}He and ^{4}He

In the meson-baryon framework, the form factors of few-body systems are convolutions of the nuclear wave functions with the form factors of the constituent nucleons, together with many-body currents and effects coming from baryons other than the nucleon. Clearly, at large momentum transfers the effects of relativity have to be taken into account explicitly. Here one can test whether or not the Q^2-dependence of the elastic form factor is compatible with the power law behavior predicted by the gluon propagator counting rule. The extension of data towards larger Q^2 is of high interest in view of the diffractive behavior as predicted by traditional models that would be absent in QCD-inspired models.

High momentum components in few-body systems

The experimental determination of the high momentum content of the nuclear wave function is a prerequisite for our understanding of interactions between nucleons at close proximity in the nuclear interior. Small but important corrections due to final state interactions and contributions from two-body currents will have to be applied to electro-induced proton knockout reactions performed in carefully selected kinematics. Results of these (e,e′p) experiments on the few-body systems at high Q^2 and high missing momentum will indicate whether at short distances a description of the nucleus in terms of nucleons is valid or a framework involving quarks and gluons has to be used. Moreover, these data will provide a benchmark test for models describing few-body systems and the off-shell corrections that are necessary to extract neutron properties from experiments on ^{2}H and (polarized) ^{3}He.

Correlations in nuclei

The study of two and multi-nucleon correlations in nuclei is proposed via inclusive DIS and nucleon knockout coincidence reactions. On one hand models describing the nucleus in the meson-baryon framework are expected to give a comparatively good description of the reaction $A + e \rightarrow e' + X$ at $x > 1$. On the other hand in this kinematic regime, high momentum quark components are being probed and models based on parton distributions predict significant contributions from multi-body correlations at $x = 1.5$ and $Q^2 > 8$ (GeV/c)^2. These data would provide a unique way to confront both approaches. Semi-inclusive $A + e \rightarrow e' + p + X$ reactions will permit one to gain better insight into the interplay between short-range correlations and two-body currents. Two-body correlations lead to nucleon pairs with high opposite momenta in the initial state. It is hoped that comparison of ^{3}He(e,e′pp) with ^{3}He(e,e′pn) data will shed light on the relative wave function of the nucleons in the correlated *NN*-pair and the importance of scalar versus tensor correlations.

The wider kinematical range that becomes accessible with the 12 GeV upgrade can be used to access the, as yet, unexplored regions of the nuclear response that are governed by violent collisions between nucleons at short inter-nucleon distances. The upgraded facility is well suited to performing the proposed experiments.

V.C.2. Hadrons in the nuclear medium and the parton-hadron transition in nuclei

This section encompasses a broad array of topics. The list includes deep inelastic scattering, color transparency, and J/ψ-N interactions. The theme common to these diverse topics is QCD. Although it is not yet possible to use QCD directly to compute observables related to these topics, its existence provokes a number of specific questions regarding effects which are not contained within the nucleon-based description of nuclei.

Quantum fluctuations in nuclear ground states lead to evanescent configurations of very high density. DIS experiments could access this region by using the higher x, Q^2 and excellent resolution available with the 12 GeV upgrade. The ability to observe scaling allows one to understand the reaction mechanism, so that a variety of measurements aimed at observing novel effects become conceivable. For instance, the difference between DIS from ^{3}He and ^{4}He could be very large. Making measurements at very high x could distinguish models that provide equivalent predictions at smaller x values.

The best opportunities to distinguish the predictions of different models involve the new ability to perform spectator-tagging measurements on the deuteron. For small values of the momentum of the backward going spectator proton, the struck neutron is essentially free. For higher proton momentum values, the struck neutron's structure could be modified. However there is no definitive model-independent signal for the onset of physics that is not contained within the nucleon-based framework.

It is also worthwhile to explore other opportunities not explicitly mentioned in the pCDR. Investigation of the nuclear dependence of semi-inclusive scattering in heavy nuclei would allow more detailed studies of the nuclear modification of the nucleon structure functions. A relatively large value of (σ_L / σ_T) or an observation of an unexpected Q^2 dependence could also reveal the presence of novel effects.

Color transparency is the reduction of initial or final state interactions. It is caused by the cancellation of the amplitudes when gluons are emitted by different quarks contained within color singlet objects. A definitive signal has been observed at Fermi Lab in the production of quark di-jets generated in pion-nucleus coherent interactions. However no clear signal has emerged in reactions involving protons. At JLab, the increase of the beam energy to 12 GeV, along with the high resolution available, increases the interest in searching for, and the chance to observe, color transparency in proton processes. The use of (e,e′p) and (e,e′pp) reactions could allow the implications of the SU(3) nature of color to be explored. Other interesting experiments involve the electro- or photo-production of pion and rho mesons.

Above threshold electro-production of J/ψ s can be investigated at 12 GeV. The production of J/ψ in nuclei is aimed at determining the J/ψ-N cross section. At present, different determinations give widely varying results. The nucleon is almost free of charm, so the reaction mechanism is of fundamental interest. The resulting cross section is also an important ingredient for the interpretation of J/ψ production processes at RHIC.

In most cases the hard scale (which determines whether hadronic or quark degrees of freedom are to be used) of the interaction between the photon and the struck object is set by the high virtuality of the photon, Q^2. However, a sufficiently high momentum transfer process might also reveal the quark aspects for real photon projectiles. In this spirit the s^{-11} scaling of the differential cross section for deuteron photodisintegration, observed at JLab some years ago, hints at the onset of partonic degrees of freedom. This behavior was observed only at large angles at a photon energy of 4 GeV and demands further clarification before being conclusive. An extension towards higher photon energies is foreseen in the 12 GeV program and will definitively determine the quark nature of this reaction.

All of the experiments discussed here could be performed using the equipment planned for the Hall A, B, and C upgrades.

V.C.3 Space-time Characteristics of Nuclear Hadronization

In DIS, the struck parton undergoes a complex process that generates hadrons in the final state. The study of this process inside the nucleus when the time required to reach complete hadronization (formation time) and the time required for the hadron to emerge from the nucleus are comparable, can yield important information about the hadronization mechanisms.

The formation time is expected to depend on the energy, ν and the momentum, Q^2, transferred to the struck quark as well as on the fraction, z , of the energy, ν, carried by the outgoing hadron. This formation time can be varied by appropriate choices of the initial kinematical conditions. On the other hand the choice of different nuclei would allow one to study the process inside nuclear volumes of different size. In a simplified picture, when the formation time is smaller than the nuclear transit time, the hadron that carries the struck quark strongly interacts with the surrounding nuclear medium, thereby degrading its initial momentum. For larger formation times, meaning that the hadronization process is completed outside the nucleus, the propagating quark and the partially-formed hadrons are expected to have little interaction with the nuclear medium.

The comparison of the production rates of various hadrons in nuclei with that rate in the deuteron, is expected to be sensitive to these mechanisms. A quantitative description requires the investigation of this reaction ratio in a wide interval of ν, Q^2 and z, as well as for different nuclear radii.

It is proposed to measure, in a wide kinematical region ($3 < \nu < 9$ GeV, $2 < Q^2 < 8$ (GeV/c)^2, $0.2 < z < 0.8$), the production rates of hadrons with definite energy fraction z in the deuteron and in nuclei ranging from ^{14}N to ^{197}Au. The comparison can be performed separately for several hadrons, charged pions, kaons, vector mesons, protons or heavier hadrons. A low statistics measurement on ^{14}N and ^{84}Kr has recently been performed at HERMES with the detection of charged pions, charged kaons, protons and anti-protons in a similar kinematical range. The data show a strong reduction of the production ratio, at large values of z and have been described by a twist-4 pQCD model. A different model describes the hadronization in nuclei in terms of gluon bremsstrahlung and predicts strong Q^2 dependence in the kinematical region accessible at JLab. An exploratory experiment has already been approved in Hall B at 6 GeV and the extension to 11 GeV will access a kinematical region above the baryon resonances region, where these models are expected to work better. Results from the proposed measurements could be important for interpretation of experiments at other facilities like HERA and RHIC.

A second proposed measurement would explore the dependence of the production yield of hadrons at large transverse momentum p_T (up to $p_T = 1.2$ GeV/c).

Different models predict that the broadening of the p_T distribution would increase linearly with the quark transit length in the nuclear medium thus showing an $A^{1/3}$ dependence. A similar effect has already been observed in the production of Drell-Yan pairs in hadron-nucleus scattering and in the di-jet production in photon-nucleus collisions. The measurement of the p_T yield in deep inelastic semi-inclusive hadron production would provide an independent set of data. This process can be investigated at JLab for different outgoing hadrons in a large range of p_T and for several nuclei.

This experimental program requires high luminosity as well as almost complete acceptance for the outgoing hadron azimuthal angle, ϕ. The detection of multi-particle final states with high efficiency is also required to reconstruct vector mesons or heavier hadrons by their decay. The experiment is clearly well suited to the JLab capabilities at 12 GeV and can be performed with an accuracy well beyond what is achievable at any other facility. In addition JLab provides access to a kinematical domain where baryon resonances dominate and it would be interesting to verify whether or not the dual parton-hadron behavior is manifested also in this process.

V.D. Probing the Standard Model of Interactions

Introduction

The Standard Model Lagrangian encompasses the strong and electroweak interactions. The non-trivial vacuum structure of QCD implies that a non-zero theta term could occur which violates the CP symmetry and leads to the "strong CP problem". The Jefferson Lab research program has been mainly concerned with using the electromagnetic interaction to probe the effects of the strong interaction in binding quarks into nucleons and nucleons into nuclei. However, the Laboratory's success in making high precision experiments involving parity violation has stimulated a program of testing the electroweak interaction through the Q_{Weak} experiment and examining the implications of the QCD vacuum using the PrimEx experiment. In that spirit, the opportunities that would be available at 12 GeV have stimulated the suggestions for new experiments discussed below.

Electro-Weak Interaction Sector

V.D.1. Parity Violating Electron Scattering

The Standard Model of strong and electroweak interactions has been broadly successful in describing phenomena in nuclear and particle physics. It is amenable to tests at the Z pole and high-energy searches for new particles. 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. Deviations from the Standard Model could signal the presence of new gauge bosons (Z), the existence of lepto-quarks or particles predicted by supersymmetric theories.

Jefferson Lab has recently entered this field by developing and proposing the proton Q_{Weak} experiment, which a previous PAC supported strongly. There are two additional opportunities presented here: parity violation in deep inelastic scattering, DIS parity, and in M∅ller scattering.

Parity Violation in Deep Inelastic Scattering
DIS parity would measure the parity violating asymmetry in electron scattering from proton and deuteron targets. The classic SLAC experiment discovered electron scattering neutral currents about 25 years ago by making the first measurement of this asymmetry. At JLab, an upgrade to 12 GeV offers many advantages over the SLAC measurement, including an increased beam current, increased target length, and a larger better-known electron polarization. This could lead to a determination of $\sin^2(\Theta_W)$ to within 0.7%, an order of magnitude improvement over the first experiment. Such a result would be extremely interesting.

The scale of the expected accuracy is comparable to that claimed by the recent NuTeV experiment that reported a three standard deviation disagreement with the Standard Model using neutrino scattering from an iron target. The use of both the proton and deuteron as targets would lead to major improvements in the eventual interpretability of the measurement. DISparity requires a beam polarization accuracy of 1%. Achieving this is a long-term goal that seems reasonable. The effects of charge symmetry breaking cause a significant difference between the distribution of d quarks in the proton and that of the u quark in the neutron, and therefore needs to be included in the analysis. The compatibility of the equipment required for this important experiment with the capabilities of the upgraded Halls needs to be confirmed.

Parity violation in M∅ller Scattering

Equally important would be a M∅ ller scattering experiment that would lead to a measurement of Q_{Weak} of the electron. In the Standard Model the parity violating asymmetry is about 4 x 10^{-8}, a value small enough to allow a precision measurement to be sensitive to new physics. There is an ongoing experiment (SLAC E158), with a final run in 2003, aimed at the same physics. The higher integrated luminosity experiment possible at JLab could confirm the final SLAC result and lead to an improvement in the measurement by a factor of two.

Such a measurement is clearly of high potential importance, especially if some deviation from the Standard Model is observed at SLAC. Performing the M∅ller experiment at the upgraded JLab facility would require equipment that remains to be specified.

Strong Interaction Sector

V.D.2. Electromagnetic Decays of Pseudoscalar Mesons, η and η' investigated through the Primakoff Effect

The physics of the scalar mesons, η and η', is related to profound issues in QCD. The axial UA(1) symmetry is explicitly broken by the full quantum theory, which through the divergence of the axial current, determines mechanisms of topological transitions, such as instantons. The $\eta - \pi$ mass difference, as well as the η' - K mass difference, are believed to result from instanton interactions. The η decay widths are closely connected to the quark masses, which are fundamental parameters of the Standard Model.

The η decay widths and transition form factors can be determined via the Primakoff effect. Knowing the η decay widths to high precision (about 1%) will further constrain the deduction of the η - η'mixing angles. This decay width is a crucial element in determining the $(m_d-m_u) / m_s$ ratio via the $\eta \rightarrow 3\,\pi$ width.

The measurement of the transition form factors at low Q^2 for the production of these mesons, will give the transition radius and new insights into the meson wave functions. Furthermore these transition form factors are important for determining the light-by-light scattering term, which enters into the calculation of g-2 for the muon.

Since the Primakoff effect in light nuclei is rather small and increases rapidly with photon energy, these important experiments need an 11 GeV electron beam. A real photon tagger and an upgraded highly granulated calorimeter are required.

There are a number of technical issues related to the measurements including the presence of backgrounds to the Primakoff effect, i.e. incoherent and coherent meson production and the unknown interference of the latter with the Primakoff effect. With the reasonable assumption that the phase does not change rapidly over 1 degree, these backgrounds could be found by carefully measuring the angular distributions of meson production as a function of photon energy and target A and Z. Relatively light nuclei will be needed to observe the coherent component directly.

There is an experiment in preparation at JLab to measure the $\pi^0 \to \gamma\,\gamma$ decay width. This will provide important insight into the experimental techniques needed for the η and η' measurement and the accuracies that can be obtained.

VI. Analysis of Experimental Equipment Requirements

In this section the PAC evaluates the major new equipment in each experimental Hall in terms of the physics program proposed for that Hall. This is followed by remarks on some non-Hall specific equipment.

VI. A. Major Hall Requirements

Hall A

The present instrumentation of Hall A consists primarily of the two high-resolution spectrometers (HRS) with maximum momentum 4 GeV/c, including a focal-plane polarimeter, which have been used for various nucleon and nuclear structure studies. Soon a large solid-angle low-momentum spectrometer (BigBite) will be added. An important part of the physics program proposed for the 12 GeV upgrade focuses on the study of the spin/flavor structure of the nucleon in the high-x region ($x \geq 0.5$) (see section V.B.1). Because the cross sections or asymmetries are often small, such studies require high luminosity and a detector with a large acceptance in momentum and solid angle, and a fairly good resolution. These requirements have led to the design of the MAD (Medium Acceptance Device) spectrometer. It consists of two combined function (quadrupole + dipole) warm-bore superconducting magnets plus a detector package including wire chambers for tracking, scintillator hodoscopes for triggering, and both time of flight and gas Cherenkov detectors, and an electromagnetic calorimeter for particle identification. Also a focal-plane polarimeter is planned for the MAD spectrometer.

The solid angle extends up to 28 msr at a maximum central momentum of 6 GeV/c, while the momentum bite is ±15%. The momentum resolution $\delta p/p$ is $1\text{-}2 \times 10^{-3}$and the angular resolution is 1-2 mrad. The spectrometer can be used at angles as forward as 12 deg. At the cost of a reduction of the solid angle to 6 msr (from the 28 msr at 35 deg.). The background of low-energy photons will be high, but manageable, and will be minimized by avoiding line-of-sight between target and detection systems and by including collimators at suitable positions.

The design of the spectrometer is well suited to the physics requirements. When used in combination with one of the HRS spectrometers (sometimes equipped with a septum magnet for smaller angle access) or a large electromagnetic calorimeter, a wide range of experiments will be possible, including form factor measurements, various unpolarized and polarized studies at high x, Deeply Virtual Compton Scattering (DVCS) and Color Transparency studies. The relatively large solid angle of MAD in combination with the high luminosity available in Hall A is very important for these studies. The maximum accepted momentum of 7.2 GeV/c will put a limit on the highest value of Q^2 or t in (semi) exclusive (e,e′h) reactions.

Hall B
The present CEBAF Large Acceptance Spectrometer (CLAS) was designed for the study of reactions with multi-particle final states. Major new initiatives for JLab at 12 GeV (for example, Section V.B.2) are the study of Generalized Parton Distributions, which are accessed through deeply exclusive reactions, and studies at high x. Such studies require two major improvements: the missing mass technique must be complemented by a more complete detection of the hadronic final state, and the luminosity needs to be increased by about an order of magnitude to 10^{35} cm^{-2} s^{-1}.

These goals will be met with an upgraded spectrometer (CLAS++) that re-uses many major components of CLAS: the large toroidal magnet, the scintillator paddles used for time-of-flight, the gas Cherenkov counters, the electromagnetic calorimeter, and most of the electronics. To obtain better forward angle acceptance, the target position will be moved up-stream, and the torus coils will be re-configured. An additional layer of Cherenkov counters, and an improved pre-shower detector combined with timing improvements to the scintillator counters, will extend particle identification to the higher momenta associated with 11 GeV beams. Improved calorimeter granularity will extend π^0/γ separation to higher energies. New calorimeters in front of the torus coils will allow events, with incomplete final state determination, to be vetoed, and will greatly improve the ability to identify rare exclusive final states. The central region will be instrumented with a new 5T solenoid magnet and a detector package with full azimuthal coverage and adequate determination of particle type, momentum, and angle (up to 135°), for both charged and neutral particles. The solenoid also serves to reduce the background rates in a new set of drift chambers, designed with smaller cell sizes to improve resolution and reduce occupancy at high luminosity.

The upgraded detector will primarily be used for measurements of GPDs through DVCS and DVMP, and measurements of the spin/flavor PDFs through inclusive and semi-inclusive electron scattering. The study of the space-time characterization of hadronization (see Section V.C.3) also requires the new capabilities of CLAS++. The acceptance of CLAS++ will permit a large portion of the phase space in electron scattering experiments with 11 GeV beams to be examined simultaneously.

Hall C
The basic detection equipment of Hall C at present consists of two magnetic spectrometers, the short orbit spectrometer (SOS) with a maximum momentum of 2.0 GeV/c, and the High Momentum Spectrometer (HMS) with a maximum central momentum of 7.3 GeV/c (due to the ± 10% momentum bite, a maximum momentum of about 8.0 GeV/c can be reached). These spectrometers have been used for a variety of studies. The physics proposed for the 12 GeV upgrade focuses on inclusive and (semi-) exclusive reactions at the highest Q^2 or t possible, in many cases in combination with precise L/T separations. For that purpose a magnetic spectrometer with fairly good resolution is needed that can

detect reaction products with the highest momentum that can be produced with an 11 GeV beam and which can reach small angles. The proposed SHMS (Super High Momentum Spectrometer) will have a maximum central momentum of 11 GeV/c (and momentum range –15/+25%), and good resolution (0.5-1.0 x10^{-3} in momentum and about 1 mrad in angle). It can be used with quite long targets (50 cm when viewed at 90 deg.). Two tunes are foreseen: one with a solid angle of 2 msr allowing central scattering angles as low as 5.5 deg. And another one of 4 msr with a minimum central angle of 10 deg.

The spectrometer consists of two quadrupole magnets (identical to the ones used in HMS) and a combined function (QD) magnet, followed by wire chambers, scintillator hodoscopes (the second plane of which is made of quartz in order to reduce the sensitivity to low-energy photons), and particle-identification detectors. The latter includes an electromagnetic calorimeter and various combinations of Cherenkov detectors plus a transition radiation detector, which together yield separation of $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ and p over the full momentum range of the spectrometer. The detector systems will be very similar to the ones used for the HMS spectrometer, which are well understood; no special difficulties are foreseen. The planned focal plane polarimeter for the HMS spectrometer will fit inside SHMS.

Altogether with the existing HMS spectrometer, Hall C will have two spectrometers that will enable the study of a variety of single-arm and coincidence reactions, such as unpolarized and polarized inclusive studies at high x including L/T separations in the valence and resonance regions, the study of the pion form factor and of nucleon elastic and transition form factors, as well as Deeply Virtual Meson Production studies.

Hall D

The goal of the new Hall D GlueX program is to discover and characterize the quark dynamics of exotic mesons (see section V.A.). Photon beams are expected to be particularly favorable for the production of exotics because the photon can behave as a virtual vector meson (a $q\overline{q}$ pair with spins aligned), and so the Hall D program is focused solely on real photon beams. Decays of exotics are expected to lead to four and five particle final states, so that careful partial wave analyses (PWA) are needed to extract the signals of interest. The convergence of such PWA is aided significantly by the use of linearly polarized beams, since linearly polarized photons are eigenstates of parity. Coherent bremsstrahlung in diamond has been selected as the production mechanism of these photons. The crystal radiator, photon tagging spectrometer and electron beam dump are housed in a separate building 75 m in front of Hall D. Collimation at the entrance to the Hall produces 3 mm beam spots with about 40% linear polarization on target.

Previous searches for exotics have been hampered by ambiguities arising from incomplete detection of final states. The combined requirements of reaching the expected mass range (1.5-2.5 GeV) while leaving the decay products with sufficient energy to be detected, and of kinematically separating the production of baryon resonances, leads to an ideal photon beam energy between 8 to 9 GeV. A very high quality beam can be produced via coherent bremsstrahlung with 12 GeV electrons.

GlueX is a hermetic detector with an effective 4π coverage for both charged and neutral particles, capable of measuring large numbers of decay products with sufficient resolution to reconstruct multi-particle final states. A 2 Tesla magnetic field is provided by a large warm-bore superconducting solenoid, recycled from the LASS and MEGA experiments. For the vast majority of events, decay products will be confined to angles forward of 90°. A veto detector located upstream of the magnet entrance will be used to veto events with backward going products. The target, located near the upstream end of the magnet, is surrounded by a vertex detector of scintillating fibers and straw tubes. Outside of this, a central drift chamber (CDC) occupying half the length of the magnet will track charged particles. Between the CDC and the magnet cryostat is a segmented barrel calorimeter, which will provide energy and time of flight information. After the CDC, but still within the calorimeter, four sets of drift chambers will track forward going charged particles. Downstream of the magnet, a Cherenkov detector will signal the presence of charged pions. A large lead-glass array, recycled from a BNL experiment, will provide forward neutral coverage. This detector package makes efficient use of existing equipment and has been optimized for the exotics search.

Rate estimates with 10^8 photons/s project to 15 kHz after the 1st level trigger, leading to 1 PB/yr. While this is a formidable rate, data acquisition and analysis plans seem well in hand. PWA will be a challenge but this issue is being actively studied by the collaboration.

Overall the design of this new facility is well optimized for investigating the photo production of mesons and studying their multi-particle decays.

VI.B. Instrumentation Requirements for Tests of the Standard Model

A number of measurements designed to test the parameters of the Standard Model of Interactions were discussed in Section V.D. The instrumentation requirements of the PV-DIS measurement will be met by the upgraded capability of Hall C. On the other hand, the instrumentation required for the investigation of PV in M∅ller Scattering remains to be specified. The investigation of pseudoscalar meson decay widths through the Primakoff Effect is explored in a proposal from the PrimEX collaboration. This very difficult measurement will require a real photon tagger and an upgraded highly granulated calorimeter. In the judgment of the PAC, the instrumentation needs of this very precise measurement require further optimization. This instrumentation is not included in the base equipment plan for the Hall upgrades.

Ancillary Equipment

Calorimeter

Large electromagnetic calorimeters are proposed for Halls A and C for detection of photons in RCS and DVCS experiments, and of electrons in exclusive measurements such as the proton elastic form factors. The PrimEx collaboration requires a larger and finer granularity calorimeter array for the detection of neutral pseudoscalar mesons. Combining the existing PrimEx, Hall A, and Hall C arrays, augmented in the central region with finer granularity PbF_2 or $PbWO_4$ blocks, could result in one or two large, general purpose calorimeters that would maximize the efficient use of resources.

Polarized targets and polarimeters

Polarized targets have been and will continue to be very important for many of the key experiments at JLab. These include targets of H, D, and ^{3}He. Efforts are underway to increase target polarization and resistance to damage caused by the beam. It is anticipated that modest improvements can be achieved.

There is a continuing need at JLab for improved precision in the measurement of beam polarization. The approved Q_{Weak} experiment requires knowledge of the polarization at the level of 1.4%. The DIS parity-violation experiment needs a precision at the 1% level. There are concrete ideas for upgrading both the existing M∅ller and Compton polarimeters to provide the needed accuracy.

VI.C. Overall Assessment of the 12 GeV Instrumentation Plan

The specifications of the various equipment upgrades as described in the previous paragraphs are well matched to the requirements posed by the anticipated physics program. The designs of the new equipment, although not scrutinized in this review, look sound. Altogether, the four Halls with their instrumentation cover the major components of the physics program described in sections IV and V (except as noted above). Moreover, all Halls will be needed in order to carry out this broad program. This is because, even if several physics topics can be investigated in more than one Hall (although never completely equivalently), the different Halls with their (upgraded) equipment each have their own specific, and sometimes unique, features. This applies especially to Hall D, which is specifically designed for the study of the exotic mesons, and as such has hardly any overlap with the other Halls. There are also other topics where only one of the Halls will make a specific contribution.

Many topics can be addressed in two or sometimes three Halls. In some cases the programs in the different Halls are more complementary, in other cases they are overlapping. For a careful evaluation of this overlap more detailed studies are needed, considering factors such as kinematic range, maximal luminosity, attainable accuracy, etc. With respect to the latter one should also take into account the beam time needed to reach a certain precision. Hall B will run at a relatively low luminosity. However this is largely compensated for (except where the cross section becomes small) by the large solid angle of CLAS++ and the fact that many reactions are measured at the same time. For studies in specific parts of the phase space, the much higher luminosity (except with polarized H and D targets) of Halls A and C will be an advantage.

Altogether the PAC is convinced that the facilities in all four Halls are essential to the pursuit of the physics program described in Section V. This conclusion is summarized in the PAC Recommendations in Section VII.

PAC Conclusions:

VII. PAC Recommendations

In evaluating the case presented for the 12 GeV facility upgrade the PAC addressed three issues:

- the impact of the science
- the match of the proposed facility to the physics program requirements, and
- the coherence of the science case as presented in the JLab reports.

In order to bring together the findings of the Committee as discussed above, the PAC makes the following four recommendations to the JLab leadership.

Physics Program

Four research areas are identified by the PAC as being essential physics drivers in the research program for the 12 GeV upgrade. We find that in two areas the science case is very strong, compelling, and well formulated.

Recommendation #1

The PAC recommends that

a) *Gluonic excitations of mesons and the origin of confinement, and*
b) *The unified description of the quark-gluon structure of the nucleon, primarily through the determination of Generalized Parton Distributions*

continue to represent the main driving motivations for the 12 GeV upgrade. The physics is well motivated and JLab has a unique opportunity to have strong impact in these areas.

Two additional topics are viewed by the PAC to also have great scientific potential. However they are not yet developed, either conceptually or technically, to the same very high degree of coherence as the first two.

For the first topic, involving the opportunity offered by nuclear systems, the PAC examined a number of research themes connected either with nuclear structure, or with the use of nuclei to study fundamental properties of Quantum Chromodynamics. These include studying short-range correlations using Deep-Inelastic Scattering at large x, testing explanations of the EMC effect using spectator tagging, observing color-transparency effects with high-resolution experiments, and making accurate measurements of nuclear hadronization processes that are of high general interest. The PAC perceived a common intellectual framework and compelling case for these initiatives in the nuclear sector.

Recommendation #2

The PAC recommends that the JLab management, staff, and User Community continue to define and formulate a coherent experimental and theoretical physics program to develop a unified description of high-density cold nuclear matter as it can be explored at the 12 GeV facility.

For the second topic, related to the Standard Model, SM, the PAC noted opportunities using the 12 GeV facility, for significant contributions or even breakthroughs, in the understanding of the foundations of the SM. Parity violation in deep inelastic scattering is a very appealing and feasible way to measure the weak mixing angle at moderate Q^2. Although of a very different nature and degree of difficulty, proposals such as Parity Violation in M∅ller scattering and a Primakoff measurement of the η meson lifetime would benefit greatly from the success of the planned Q_{weak} and Primakoff-π^0 experiments with the present facility. The instrumentation required for the next generation of SM experiments is not generally included in the Hall upgrade documents.

Recommendation #3

The PAC recommends that the JLab management, staff, and User Community *continue an aggressive study of the feasibility and technical requirements of measurements that test the Standard Model: in the electro-weak sector as they relate to parity violation in deep-inelastic scattering, as well as the weak charge of the proton and the electron, and in the strong sector as they test the strong interaction Lagrangian through investigation of the radiative decay of* π^0, η, *and* η' *mesons.*

Experimental Facilities

The specifications of the proposed equipment for the upgrades to the detectors in Halls A, B and C, and the new Hall D facility, are well matched to the exciting physics program that has been proposed. On the whole, the designs of the proposed equipment are developed in considerable detail. A few items related to Recommendation #3 are not included in the basic upgrade instrument package.

Recommendation #4

The PAC endorses the overall plan for the proposed major new instrumentation as being required to implement the new physics program and therefore recommends that the JLab management pursue the construction of the major components in all four halls as being critical to the success of the 12 GeV Upgrade program.

In addition the PAC brings the following specific issues to the attention of the JLab management regarding the formulation and design of the experimental instrumentation:

-A very interesting experiment requiring a specialized tagging system (not included in any of the Hall upgrade packages) has been proposed by the PrimEx collaboration. However, the present design is still in an early stage of development. The PAC suggests that the collaboration continue to develop the design and carry out extensive simulations of background processes.

-A very interesting test of the Standard Model through M∅ller scattering has been proposed, although the required equipment has yet to be identified. The PAC suggests that the collaboration develop a detailed equipment design for this difficult but important measurement.

-Several experiments have proposed electromagnetic calorimeters. The PAC suggests that management investigate the feasibility of constructing a minimum number of calorimeters with sufficient flexibility to accommodate these needs.

-Several experimental programs would benefit from a transversely polarized target in CLAS++ and from a tagged real photon facility in one of the existing Halls. The PAC suggests exploring the feasibility of developing these capabilities.

-The program on meson dynamics in Hall D faces challenges from baryon backgrounds. Potentially, these could be significantly reduced in reactions on $^{4}He/^{3}He$, provided that the recoil nucleus could be detected. The PAC suggests that the technical feasibility of this option be explored.

VIII. Conclusions

Overall it is the judgment of the PAC that the envisioned JLab Upgrade offers an outstanding opportunity for exploring new and fundamental physics issues of great interest to the community of nuclear and particle physicists. These include two areas of study which provide strong and compelling motivations for the upgrade, namely:

a) The investigation of meson dynamics using an intense polarized photon beam and a hermetic detector required to identify the relevant many-body final states, and
b) The measurement of nucleon structure and its interpretation in terms of Generalized Parton Distribution functions, by exploiting the enhanced momentum reach, forward angle capability, and large acceptance, together with the high luminosity and polarization capabilities of the upgraded facility.

Furthermore, while less developed at present, the PAC further recommends

c) The exploration of high density nuclear matter by using the increased energy and precision in a program of studies of cold nuclear matter at high densities, and
d) The further development of measurements to test the Standard Model of interactions and its parameters. The latter can be probed in the electro-weak sector through measurement of parity violation in DIS and the weak charge of the proton and the electron, and in the strong sector through investigation of radiative production and decay widths of the π^0 (in process), η, and η'mesons.

In many respects the new experimental facilities will be unique in the world. They will also impact issues raised at other facilities available to the nuclear and particle physics community. Therefore the PAC enthusiastically endorses the JLab 12 GeV Upgrade in view of the timeliness and high impact it can have on physics issues of concern to a broad spectrum of the nuclear and particle physics community.

Appendices

Appendix A. Reports and Supporting Documentation.

The following reports were used as supporting material by PAC XXIII in reviewing the Proposed JLab 12 GeV Upgrade.

1. Hall A 12 GeV Upgrade, Pre-Conceptual Design Report, Hall A Collaboration, December 2002

2. The Hall B 12 GeV Upgrade Pre-conceptual Design Report, Hall B Collaboration, December 2002

3. Conceptual Design Report, Hall C 12 GeV Upgrade, Hall C Collaboration, November 2002

4. The Science of Quark Confinement and Gluonic Excitations, GlueX/Hall D Design Report, version 4, The GlueX Collaboration, November 2002

5. Electromagnetic Properties of Pseudoscalar Mesons via the Primakoff Effect at 11 GeV, The PrimEx Collaboration, December 2002

6. The Science Driving the 12 GeV Upgrade of CEBAF, Jefferson Lab, February 2001

Appendix B. Charge to the PAC XXIII 12 GeV Upgrade Review

1) Comment on the intellectual framework presented for the 12 GeV pCDR. Is this the best way to present the science case to DOE and to the larger nuclear physics community? Are there flaws or omissions in the framework?

   The PAC response is presented in Sections II, IV, and V of this report.

2) Review the research programs that are under consideration for being highlighted in the executive summary of the pCDR. Do they represent compelling science that must be done to advance our understanding of nuclear physics? At what level should they be included in the executive summary?

   The PAC review of the research program is presented in Section V. The resulting PAC recommendations are presented in Section VII.

3) Have we omitted any key science initiatives that could be supported by a 12 GeV electron beam?

   Several opportunities for an extended research program are described in Section V.

4) Is the experimental equipment proposed well matched to the key physics experiments motivating the upgrade? In cases where an experiment or program is proposed for more than one set of equipment, are the differences in capability and physics reach of the equipment essential for getting all of the physics, important for getting as much physics as possible, or simply useful in that, for example, an experiment could be done somewhat faster with one hall equipment compared to another?

   These issues are addressed by the PAC in detail in Section VI.

Appendix C. Agenda of the January 17-22, 2003 Meeting of PAC XXIII

The 45 minute talks are 25 minutes plus 20 for discussion; the 30 minute talks are 18 minutes plus 12 for discussion)

Friday, January 17, 2003

0830-0930	Executive Session (L104)	
0930-1000	Introduction	L. Cardman
1000-1015	Coffee Break	
1015-1115	Confinement: The Search for Hybrids and Meson Spectroscopy and Additional Physics Topics: (2) Other Topics in Meson Spectroscopy (ss-bar Mesons, etc.)	A. Dzierba
1115-1200	Hadron Structure: (1) Valence Quark Structure and Parton Distributions	Z.-E. Meziani
1200-1330	Lunch (executive session)	
1330-1415	Hadron Structure: (2) The Generalized Parton Distributions as Accessed via Deep(ly) Exclusive Reactions	V. Burkert
1415-1500	Hadron Structure: (3) Form Factors and Polarizabilities - Constraints on the Generalized Parton Distributions	P. Stoler
1500-1530	Coffee	
1530-1550	Hadron Structure: (4a) Other Topics in Hadron Structure: Duality	T. Keppel
1550-1610	Hadron Structure: (4b) Other Topics in Hadron Structure: Q2 Evolution of the GDH Sum Rule	G. Cates
1610-1630	Hadron Structure: (4c) Other Topics in Hadron Structure: Single Spin Asymmetries	H. Avagyan
1630-1700	Additional Physics Topics: (4) Space-time Characteristics of Nuclear Hadronization	W. Brooks
1700-1830	Executive Session	

Saturday, January 18, 2003

0900-0930	Nuclear Structure: (1) Probing the Limits of the Nucleon- Based Description of Nuclei	L. Weinstein
0930-1000	Nuclear Structure: (2) The Parton-Hadron Transition in Nuclear Physics	H. Gao
1000-1015	Coffee Break	
1015-1045	Nuclear Structure: (3) Hadrons in the Nuclear Medium	J. Arrington
1045-1115	Additional Physics Topics: (1) Standard Model Tests (new)	P. Reimer
1115-1145	Additional Physics Topics: (3) Spontaneous Symmetry Breaking (Primakoff Expt.)	A. Gasparian
1145-1330	Executive Session w/ Lunch Adjourn	

Sunday, January 19, 2003

AM	Travel to Outer Banks	
Noon	Lunch at Outer Banks	
1330-1500	Introduction/Discussion of “How to Proceed”	
1500-1730	12 GeV Physics Discussion I	

Monday January 20, 2003

0900-0945	Hall A Plans	K. de Jager
0945-1030	Hall B Plans	V. Burkert
1030-1100	Coffee Break	
1100-1145	Hall C Plans	R. Ent
1145-1230	Hall D Plans	E. Smith
1230-1400	Lunch	
1400-1500	Hall “Orthogonalization”	L. Cardman
1500-1530	Coffee Break	
1530-1800	Physics Discussion III	

Tuesday January 21, 2003

0830-1200	Discussion and Report Writing	
1200-1330	Lunch	
1330-1730	Discussion and Report Writing	

Wednesday January 22, 2003

0830-1100	Discussion and Report Writing	
1100	Summary	P. Barnes
1200	Lunch and Adjourn	

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