Special PAC 18 Review of the Science Driving the 12 GeV Upgrade

Executive Summary

The Jefferson Laboratory experimental program is producing important new insights into the properties of hadrons and nuclei, especially at the smallest distance scales. The future experimental program is being shaped by these insights, along with recent advances in theoretical understanding of the nuclear many body system and non-perturbative aspects of QCD, to take maximum advantage of new opportunities. This has led the electron scattering community to conclude that qualitatively new discoveries, unforeseen at the time of conception of CEBAF, lie just beyond the scope of the present accelerator. The combination of continued progress in the development of the superconducting radio-frequency accelerator technology, and foresight in the original implementation of the accelerator makes an energy upgrade of the facility to 12 GeV well matched to the science challenges and very cost-effective.

The laboratory and the user community have developed an impressive scientific case that demands this new capability. The Jefferson Lab Program Advisory Committee was charged by the laboratory to review this science, and to review the plans for the associated experimental equipment.

The committee concludes that an outstanding scientific case has been identified which requires the unique capabilities of the JLAB 12 GeV upgrade. The results of these experiments are likely to significantly change the way we think about nuclear physics and the strong (non-perturbative) limit of QCD. Two major new thrusts can produce definitive results: the experimental verification of the origin of quark confinement by QCD flux tubes as predicted by lattice gauge calculations, and the determination of the quark and gluon wave functions of the nuclear building blocks. The full technical capabilities of the upgrade are required for this progress. New research domains are also opened up that show great promise in leading existing research efforts to new levels of understanding.

The proposed experimental equipment are well suited to addressing these new physics opportunities. The choices capitalize on the powerful existing equipment at the laboratory without compromising the physics goals.

The Program Advisory Committee was excited by the research potential that the 12 GeV upgrade makes possible. The scope of the upgrade is very well matched to the problems we see driving the field for the next decade. The time has come to bring these opportunities to nuclear physics.

Introduction

As the scientific program at Jefferson Lab blossoms, the Jefferson Lab User community and the laboratory have become convinced that a compelling scientific case exists for a significant upgrade of the facility to 12 GeV beams. Progress in accelerator technology and foresight in the initial planning of the laboratory have combined to make this upgrade very cost-effective. The JLAB community has, over the past six years, extensively evaluated their options for the future and concluded that this is the best major step forward for studies of hadrons and nuclei with electromagnetic probes. In the past year, a series of workshops and working groups have made detailed studies of the science issues and the instrumentation required. A list of these activities is given in Appendix 1.

The laboratory has asked PAC 18 to review the science driving the 12 GeV upgrade with the following charge:

Jefferson Lab requests the PAC18:

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

2) Review the experiments that are under consideration for being highlighted in the white paper. Do they represent compelling science that must be done to advance our understanding of nuclear physics? Have we omitted any key science initiatives that could be supported by a 12 GeV electron beam?

3) Is the experimental equipment proposed well matched to the key physics experiments motivating the upgrade?

The membership of the PAC is given in Appendix 2 and the agenda of presentations for the special review is given in Appendix 3.

In December 1999, a PAC subcommittee, chaired by David Cassel, reviewed one principle motivation for the upgrade, a definitive search for meson states with exotic quantum numbers using real photon beams. The subcommittee concluded this was very high priority physics that could uniquely be done at JLAB and that a technically sound design of the experimental equipment existed to demonstrate that the scientific potential could be realized. With this report in hand, this PAC did not review the meson spectroscopy program in detail, but did consider how it would fit into the presentation of the scientific case for the upgrade.

Technical Scope of the Upgrade

The science case discussed below requires electron beams of 12 GeV to produce the 9 GeV polarized photon beams required for the meson spectroscopy program and electron beams of near this energy to make a major extension of the kinematic regime accessible at the laboratory. The performance of superconducting r.f. cavities has continued to improve and with cavities of the present capability, the linac sections can be upgraded with limited additions and replacements to achieve 1.1 GeV acceleration in each linac. With modest improvements in the recirculation arcs, 11 GeV beams (with a total beam power of 1MW) could be delivered to the present experimental halls. The addition of one new set of arc magnets allows the beam to be recirculated for one further pass through a linac section and a low power beam would be extracted into the photon tagger system for a new experimental hall (Hall D) at 12 GeV, a hall dedicated to meson spectroscopy with polarized photon beams.

This concept for the Jefferson Lab upgrade provided the technical basis for the PAC consideration of the scientific issues. In each case, it was found that the scope of the upgrade was well matched to the breakthrough scientific thrusts.

Response to First Charge

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

The white paper draft presented three primary areas where a 12 GeV upgrade would make a major impact on our understanding of hadronic physics and its QCD substructure. The PAC reviewed each of these areas in turn and found all of them sound. The following comments summarize these deliberations

- *The experimental verification of the origin of quark confinement by QCD flux tubes.*

For the first time in three millennia of reductionism, science has encountered a degree of freedom that cannot be isolated. The properties of strong QCD and the nature of confinement are among the outstanding unresolved problems in physics. At the turn of the 21st century there is strong evidence from theory and computation that confinement of quarks is intimately due to the development of flux tubes between them. This seminal insight awaits experimental confirmation; its wider implications are yet unknown.

As matter is heated, theory predicts that the gluonic degrees of freedom in the flux tubes must be excited, the first manifestations of which will be the appearance of "hybrid" states in the hadron spectrum. Predictions for the energy scale of their production have now converged, and estimates of their characteristics and production rates in electromagnetic processes are now rather precisely predicted. In particular the existence of exotic combinations of spin-parity-charge conjugation (J^{PC}) quantum numbers among the hybrid mesons will aid their identification. These particular exotic states have their valence quark-antiquark content coupled to spin-1 and are thereby especially suited to production by photons, both real and virtual, in diffractive processes. A 12 GeV upgrade at CEBAF will provide unique means to produce these states, separate them from background and establish a new spectroscopy in QCD.

- *The determination of the quark and gluon wave functions of the nuclear building blocks.*

Historically, information on the parton structure of hadrons has predominantly been restricted to knowledge of probability distributions for gluon and quark flavors and spins. Recently, theoretical advances have shown that "off forward" (or generalized) parton distributions may be accessed in deep exclusive processes under suitable kinematic conditions. The beam energy and quality of the proposed upgrade would offer an extensive program of investigation in this kinematic regime and reveal details of hadron structure that go far beyond what has hitherto been available. Exclusive reactions such as deeply virtual Compton scattering and exclusive meson production provide new and unique information on the quark-gluon wave functions of the hadrons.

One limit of the generalized parton distributions is the electromagnetic form factors of the hadrons. The pion is the lightest hadron and of fundamental importance in its connection to chiral dynamics. While significant measurements of the charged-pion form factor are underway at JLab, it is only at the momentum transfers available with the upgrade that these measurements will cleanly test the applicability of perturbative QCD in exclusive reactions and the quark-antiquark distributions of the pion.

Measurements with the upgrade can give unique information on the spin and angular momentum structure within nucleons. This will touch on one of the great enigmas discovered in recent years, namely the nucleon spin problem, which in turn has focussed attention on the general question of spin and flavor correlations within hadrons. These questions have become particularly sharp in the extreme valence limit, $x \rightarrow 1$ where the role of symmetry breaking, gluon dynamics and other aspects of QCD can be uniquely determined with data in this hitherto poorly explored kinematic region. A 12 GeV electron upgrade at JLab will for the first time provide high precision deep inelastic scattering data for $x>0.65$.

- *Open important new research domains in areas already under investigation.*

The PAC encourages the community to be extremely cautious in including many topics in this area in the highest level synopsis of the physics case. All of the research thrusts broken out in this bullet were regarded as excellent research programs for an existing facility. All would greatly benefit from 12 GeV beams and should be included in the 12

GeV white paper and executive summary. However the laboratory must be wary of being viewed as proposing to do “more of the same”, or of having promised “more than could be delivered” in the past. When these experiments are prime foci of work at the present machine, the concerns are that they might not appear sufficiently fresh or the ongoing work might resolve the issues. In other instances the interest is very high but the scientific underpinnings would need more work to be highlighted. Two experiments reviewed by the committee definitely require higher energy beams and did resonate with the PAC members: the $x>1$ study of short-range nuclear correlations and the coupling of the η and η' mesons to photons. These would be the examples the PAC would pick to support the third bullet in a one page synopsis of the physics case. We encourage the community to continue to sharpen the case for other physics programs under this broad thrust.

The increased energy and unique beam qualities at CEBAF would allow a substantially new study of nucleon correlations by measurements in the $x>1$ region. The parton structure that could be generated by such correlations would become accessible at sufficiently large momentum transfers. This could thereby provide important insights into high density, multi-nucleon configurations in nuclei and more general insights into their short distance structure. In addition, the newly accessible kinematic regions will provide opportunities for investigating the transition from the nucleonic picture of nuclei to one based on quark degrees of freedom.

The η' has been an enduring mystery that can be probed with the new facility. This touches on a number of fundamental issues such as anomalies in QCD, the nucleon spin problem and the role of glue in mesons. By means of the Primakoff mechanism, the 12 GeV facility would open investigations of both η and η' coupling to photons as the existing facility did for the π^0. The ability to vary the virtuality of one of the photons (from the scattered electron) can provide a qualitatively new class of information on the substructure of the η and η' mesons.

Response to the Second Charge

2) Review the experiments that are under consideration for being highlighted in the white paper. Do they represent compelling science that must be done to advance our understanding of nuclear physics? Have we omitted any key science initiatives that could be supported by a 12 GeV electron beam?

In this section the PAC will review the individual experiments that were presented as the basis of the 12 GeV program. The order of the discussion simply follows the order of the presentations. The PAC has tried to provide constructive criticism in each case to help guide the users to strengthen the scientific and technical issues.

Several experiments highlight the unique contribution that can be made to studies of the valence quark structure of the nucleon. Indeed, the great discovery of three decades ago was the existence of the quark substructure of the hadrons. The quark-parton model emerged from the early inelastic electron scattering experiments as the physical picture of nucleon structure. In those early days, studies of the scaling features of the data predominated, with studies of the Q^2 dependence made mostly at the highest Q^2 values available. Bjorken scaling was the predominant feature of the landscape, down to surprisingly low values of Q^2. Logarithmic scale breaking soon superceded the concept of Bjorken scaling, and experiments pushed to the highest energies to study these logarithmic deviations. Because of the history of ever increasing energies and Q^2, the high-x region of kinematics we associate with the valence quarks in the nucleon, x>0.5, was hardly covered. The high-energy beams available lacked the intensity and resolution needed to investigate the quark-parton model at high x. The 12 GeV upgrade at Jefferson Lab will be ideally suited to study the valence quark distributions in the nucleon in detail and with considerable precision. The following two sections discuss several "must do" measurements that could substantially strengthen our understanding of the nucleon in the valence quark region of the quark-parton picture.

- **The d/u Quark Ratio in the High-x Range**

Raising the energy to 12 GeV opens up the high-x region for inelastic electron scattering studies and a unique opportunity for new information on nucleon structure. Measurements of the deep inelastic scattering (DIS) structure functions F_2^n and F_2^p at high x can be readily interpreted in terms of the ratio of the quark distribution functions, d(x)/u(x). Textbook discussions of the quark-parton model often contain plots of the ratio, $F_2^n(x)/F_2^p(x)$ up to x of 0.8 obtained from comparisons of deuteron and proton data. However, the binding energy and Fermi motion effects must be correctly taken into account to extract the value of F_2^n for a free neutron. These corrections can be important, since they can significantly modify the uncorrected values of F_2^n . In addition, the discovery of the so-called "EMC Effect" in DIS (for A > 3) has shown that the quark distributions are modified by the nuclear medium and led to the consideration of other nuclear effects. This has brought into question the validity of the wave functions used for the deuteron as well. If there are uncertainties in the deuteron wave function, theoretical errors associated with the uncertainties in the deuteron are large for the ratio F_2^n/F_2^p at high x, (x>0.6.)

Jefferson Lab, with a 12 GeV Upgrade, can significantly improve on the uncertainties in $F_2^n(x)/F_2^p(x)$, and therefore on d(x)/u(x) at high x, by a comparison of deep inelastic scattering from ^3H and ^3He targets. Since the binding energies and density distributions are nearly the same for these two nuclei, the nuclear effects should be quite similar allowing a more model independent extraction of F_2^n /F_2^p.

- **A_1^n, the asymmetry in inelastic scattering of longitudinally polarized electrons from a polarized neutron target**

QCD makes a clear prediction that the asymmetry of polarized electron scattering on a polarized neutron target, A_1^n, must approach 1 as x approaches 1.0. However the existing data, of reasonable quality only below x of 0.4, find A_1^n to remain negative or consistent with zero. Measurements of A_1^n must be extended to high enough x to determine the x=1 value. More generally, analysis of $\mathbf{A_1^n}$(x) and the corresponding asymmetry data for the proton, A_1^p(x), have resulted in the "spin crisis" (as seen by the failure of the Ellis-Jaffe Sum Rules) and in the confirmation of the Bjorken Sum Rule, a test of QCD. Currently models for $\mathbf{A_1^n}$ are being used in the high-x region to evaluate the sum rules. High-x data on $\mathbf{A_1^n}$ (x) are desirable to refine the *experimental* evaluation of the sum rules, to refine the models used, and primarily to study the relationship between current quarks and constituent quark models of the nucleon. If $\mathbf{A_1^n}$ is not found to approach 1 as x approaches one, this will be a dramatic refutation of our current understanding of the quark model of nucleon structure.

The extraction of A_1^n requires that corrections for the binding of the nucleons be made. This is a straightforward matter for most values of x, but other admixtures in the ^{3}He wave function, such as low-probability Δ components could become relatively more important at the highest x values. The collaboration needs to investigate this point in more detail.

Jefferson Lab has the ideal experimental conditions to contribute to the large x regime. An experiment for 6 GeV and $x < 0.5$ is being planned for Hall A. The 12 GeV upgrade would allow for much improved measurements in the deep inelastic scattering region that cover up to $x = 0.75$, and with significantly improved errors over those of a 6 GeV run. A 12 GeV upgrade would make a definitive measurement of $\mathbf{A_1^n}$(x) possible and would provide tests of quark structure which could not be done anywhere else with comparable quality.

The range of kinematics from a 12 GeV Upgrade covers resonances of the nucleon in the high-x range. Considerable interest in the behavior of the resonances exists, including the possibility for better understanding of duality and the possibility of using these data to extrapolate to the $x = 1$ limit. The application of duality will be discussed in more detail in a subsequent section.

While not presented to the PAC, the situation is somewhat similar for the corresponding asymmetry for the proton, A_1^p(x). The data extend out to $x = 0.7$, but with rather large errors for $x > 0.5$. A program to study the valence quark distributions should include measurements of A_1^p(x) at large x for the same purposes mentioned for the neutron asymmetry. In the case of A_1^p(x), the data are in general agreement with quark model calculations, but improvement in these data would be useful for refinement of the spin structure functions, for studies of the nucleon resonances, and for the behavior as x approaches 1. An improved measurement of A_1^p with the 12 GeV Upgrade at Jefferson Lab would support the unique opportunity to greatly improve our confidence in the constituent quark model understanding of the nucleon.

- **Deep exclusive scattering**

Recent theoretical advances suggest that there are new approaches to probe the structure of the nucleon. The generalized parton distributions for the proton and the neutron can be experimentally determined by studying deep exclusive scattering processes in various final states. The measured cross sections are, in general, dependent on four universal (for a given target) structure functions for each quark flavor. They are functions of momentum fraction of the parton before the interaction, the momentum fraction of the parton after the interaction, and the square of the momentum imparted to the final state baryon. Accurate measurements of these structure functions in the scaling region and over a broad range in the kinematic variables can isolate the individual parton distribution functions. The generalized parton distributions contain a wealth of information about the transverse momentum and angular momentum carried by the quarks in the proton which is not available in the quark distribution functions measured in deep inelastic scattering. For example, an important sum rule connects the integral over two of the structure functions with the total angular momentum (spin plus orbital) carried by the quarks.

The application of perturbative techniques is expected to be most straightforward for deeply virtual Compton scattering where the elementary verticies are purely electromagnetic and this process will be the benchmark for deep exclusive scattering studies. Exclusive virtual photon-induced meson (π,ρ ...) production will test the universality of the generalized parton distributions expected from factorization and permit the separation of the individual structure functions. It is believed that at least 10 GeV is essential for beginning such an exploratory program. It would represent a new basic approach for studying QCD and parton distributions in particular and shows great promise for providing fundamental **new** information on the parton wave functions. Only the data can verify how extensively one can apply these techniques. The upgrades proposed for the CLAS detector have been motivated in part by the requirements for this class of experiments.

- **Parton-Hadron Duality**

Recent experimental results from JLAB have revitalized the subject of duality between quark and hadron descriptions of inelastic electron scattering. This significant progress has encouraged the community to consider new applications of duality concepts in hadronic structure. The PAC believes that in order to study duality and its manifestations in a quantitative way, the two following items have to be addressed:

1) A precise averaging procedure of the resonances has to be defined, both on experimental and theoretical grounds. This procedure has to be first applied in the kinematic region in Q^2 and W where scaling is established.

2) This procedure can then be extended to the lower Q^2 and W regions and to neutron and polarization observables.

The issue of the W lower limit commonly used as a frontier for the scaling domain is an important one, and the somewhat arbitrary values in common use will be better defined when duality is understood, and the transition between the “resonances” and the scaling region can be explained.

The primary advantage of a 12 GeV beam for studying duality itself is the possibility of greater overlap between the resonance region and the scaling region at this laboratory. Sufficient data can be taken with 6 GeV beams to address the proper averaging procedure in F_2 or g_1 relative to higher Q^2 data from other laboratories. The extension of the studies to semi-inclusive data or to σ_L/σ_T will profit much more, in a second step, from the 12 GeV upgrade. If duality were demonstrated to be understood, it will provide a very appealing tool for high-x studies at 12 GeV. The resonance region will become very useful in obtaining information hard to get elsewhere.

- **Short Range Nuclear Correlations Using DIS**

The suggestion to use DIS at x>1 to search for super-fast quarks in nuclei as a signature of short range correlations (SRC) is a very important one. Certainly the observation of SRC has long been a goal of traditional nuclear physics, but quantitative evidence for correlations beyond the mean field has been difficult to obtain. Understanding the reaction mechanism of knockout reactions in the kinematic regime where correlations are expected to be visible has proved difficult. Two nucleon knockout experiments are now possible, but it remains to be seen whether they will prove easier to interpret. In any case, a clear experimental signature of SRC in the the parton sector would be highly desirable.

Inclusive DIS appears to provide just such a method. In the scaling regime, which is expected to be achievable at 12 GeV even for moderately heavy nuclei, the reaction should be straightforward to interpret in terms of parton distributions. At x>1, these are "super-fast" partons. In the calculations shown, these predicted distributions are interpreted as evidence for two-body and many-body correlations. The signatures in the calculations are dramatic and unmistakable, almost too good to be true. It is important that the theoretical interpretation of the predicted super-fast partons in terms of the long sought short-range correlations be reviewed as rigorously as possible. While the PAC finds this interpretation eminently plausible, this subject has been fraught with problems of interpretation for so long that the initial reaction of outsiders could well be skeptical. Critical theoretical commentary should be sought.

Deep inelastic scattering directly measures the distribution of the light front momentum fractions, ξ, of the partons. The physical effect here is that the many-body correlations result in significant enhancements of the light front distributions of heavy nuclei for $\xi>1$. The light front distribution should not have a strong Q^2 dependence and an observation of this weak dependence will demonstrate one is in the scaling region. The physics case would be much clearer if it were recast in terms of the ξ dependence of the ratio of nuclear distributions to separate the Q^2 dependence from the quark momentum dependence. The Nachtmann variable, ξ, rather than x, is the appropriate experimental measure of the light front momentum fraction. It is the large Q^2 range available at 12

GeV that gives us confidence that the scaling region will be reached in these measurements. As was previously discussed in extracting nucleon structure functions from three body systems, the existence of other objects such as Δ's or more exotic components can cloud the interpretation, but these would also signal fascinating physics. It is important to directly relate the scale of the predicted correlations to the scale of correlations sought in knockout reactions at lower energies. A plot of n(p) for the mean field alone, then with two-body and then many-body correlations would be helpful.

- **Short Distance Nuclear Structure --Form Factors of Light Nuclei at Large Q^2**

The main features of presently measured form factors of the few nucleon systems (A=2,3,4) are fairly well described in the standard framework of interacting nucleons and mesons. Several models based on the relativistic approach of the impulse approximation including meson exchange currents and isobar configurations have proven to be relatively successful.

Extending the measurement of the form factors to much larger Q^2 would provide fundamental nuclear physics data that would test our present knowledge of the NN interaction at short distances. It is of high interest to investigate a much larger Q^2 domain to search for the diffractive behavior predicted by traditional models that would be absent in QCD-inspired models. The parallel investigation of ^3H and ^3He elastic form factors would also permit disentangling the isoscalar and isovector contributions.

From an experimental point of view, the rapid decrease of the elastic cross section with increasing Q^2 will require high beam energy and large acceptance spectrometers with energy resolution good enough to separate the reactions of interest from competing channels. CEBAF at 12 GeV with the proposed instrumentation would be able to accomplish this program, increasing the Q^2 range by about 50% relative to the plans for experiments at 6 GeV.

The PAC agrees that this is an important investigation to push to the highest possible momentum transfers. However, a broad kinematic range remains to be examined at 6 GeV and there is real potential for new discoveries in those experiments.

- **The electromagnetic form factor of the pion, F_p**

The pion is the lightest hadron. Its relation to broken chiral symmetry is a matter of considerable theoretical interest. Understanding its structure has fundamental significance and therefore the electric form factor of the charged pion is a quantity of prime importance to our understanding of hadronic structure. A 12 GeV upgrade to CEBAF will offer the possibility to measure this form factor to good precision out to $Q^2 = 6$ $(GeV/c)^2$ for the first time. This in turn offers the best possibility to study the transition between the dominance of `soft' and `hard' processes in the dynamics, and to learn where the perturbative QCD limit may be reached.

The pion form factor cannot be measured directly – for practical purposes it must be deduced from a careful study of the longitudinal and transverse cross sections for p(e,e’ p^+)n in kinematics selected to enhance the sensitive t-channel process and to minimize background contributions. The t-channel longitudinal cross section dependence is then fitted to the best available theoretical model to determine the value of F_p . The F_π collaboration has applied this technique at CEBAF to determine the pion form factor out to 1.6 $(GeV/c)^2$ and assesses the theoretical uncertainty in extracting F_p from the data to be of order 6% in this range. A 12 GeV machine will open up a new kinematic range to the experiments, allowing them to be performed at higher W and low |t| at higher Q^2 which should minimize the theoretical uncertainty in the results. It will not be possible to fully assess the theoretical systematic error until the program of longitudinal and transverse measurements has been carried out, but current estimates by the collaboration indicate that F_p can be measured to $\pm$ 7%, with the theoretical uncertainty dominating the error bar. The committee cautions that additional theoretical work needs to be done to fully assess the model uncertainties with the aim of extracting F_p from the data with the best possible precision. This measurement will be an important contribution to our knowledge of hadronic structure and is ideally and uniquely suited to the CEBAF physics program with the 12 GeV energy upgrade.

- **Production of J/y mesons near threshold.**

The 12 GeV upgrade reaches one major production threshold compared to the existing facility, the charm quark threshold at 8 GeV. The large mass of the charmed quark immediately provides a short distance scale for the QCD dynamics. The J/ψ meson is an inherently small object and high momentum scales are involved in its production at these energies. With the interest in the interaction of compact objects aroused by color transparency studies and the need to understand J/ψ-nucleon interactions in heavy ion collisions, it is unfortunate that the J/ψ-nucleon cross section is not well determined by existing data.

The existing data on low energy electroproduction of the J/ψ’s are extremely sparse and are our only source of information on J/ψ-nucleon interactions. Since the nucleon contains precious little c-cbar content, quark exchange is strongly suppressed in J/ψ-nucleon interactions and one has the opportunity to directly examine the role of gluon exchange. The existing data hint that the energy dependence of J/ψ photo-production changes dramatically near threshold and this has been suggested to be a signal of a three gluon exchange mechanism taking over from the two-gluon exchange mechanism that dominates in higher energy exclusive channels.

Exploratory experiments addressing both the photoproduction mechanism on the proton target and the nuclear dependence of J/ψ production can be performed at the JLAB upgrade with the proposed experimental equipment. Measurements of the energy dependence of the nuclear effects are essential. A dedicated electromagnetic calorimeter electron detector would allow significant increases in the statistical precision and kinematic range of these experiments. Other more speculative programs such as the search for hidden color states using J/ψ production could also become possible.

While the current ideas in this program are quite focused, we expect that the underlying physical domains are sufficiently different than those of light quark systems that a number of new research initiatives are likely to emerge here in the future.

- **Precision Measurements of the electromagnetic properties of pseudoscalar mesons at 11 GeV using the Primakoff effect**

The physics questions addressed by the proposed measurements are very important and appealing and follow two main axes:

1) Precision measurements of the η and η' widths for 2-γ decay.

2) The transition form factors for π^0, η and η' decays into $\gamma\gamma^*$.

Both these lines address the low energy manifestations of QCD in the non-perturbative regime for which chiral theory is appropriate and the π's and η's are the Goldstone bosons. The study of the π^0, η and η' mesons therefore provides a powerful tool to better understand the low energy behavior of QCD.

A precise measure of point 1) will provide a clean means of getting the mixing angle θ between the η_8 and η_0 flavor states, and of extracting the $f_{\eta 0}$ parameter. A comparison of these data with other approaches could also lead to establishing the possible gluonic content of the η'.

The form factor measurements might be even more important, although they are quite difficult. The existing π^0 data do not even agree on the sign of the form factor slope, and η and η' data do not exist. The intercomparison of these 3 form factors will lead to very valuable information on the quark-gluon content of these mesons. The PAC recognizes the peculiar nature of the η' meson which motivates the interest in its study, but has some concerns on the applicability of chiral perturbation theory for such a heavy object.

This experimental program requires very challenging techniques, especially in the performance of the recoil detector. The PAC strongly encourages work to assure the feasibility of this promising program.

- **Color transparency**

Color transparency is the vanishing of final or initial state interactions at high Q^2 in nuclear quasi-elastic scattering, or more generally in hard color coherent processes. This vanishing is predicted by QCD for such reactions that proceed by the formation of color neutral, point-like configurations (PLC). The effects of gluons emitted from a PLC cancel in coherent processes. But the necessary values of energy and momentum transfer must be determined experimentally because non-perturbative effects become relevant as the PLC expands as it moves through the nucleus. There is recent very strong evidence for color transparency at Fermilab in the observations of coherent di-jet production in pion induced nuclear scattering, and there have been indications observed in ρ meson production experiments. There is also evidence from (p,pp) reactions at Brookhaven, in which the transparency (relative cross section) is seen to rise rapidly and then fall as energy increases. The fall is believed to be due to an interference effect that would not occur in electron proton interactions. The discovery of color transparency at the kinematics available to Jefferson Lab at 12 GeV would demonstrate the existence of PLC as an important feature of the nucleon form factors. Furthermore, there would be significant implications for the structure of nucleons bound in nuclei. The PLC in the nucleon wave function would not interact with the attractive nuclear potential and therefore their probability amplitude would be reduced. This would correspond to a suppression of high momentum components of the nucleon wave function that would have consequences for diverse measurements including deep inelastic scattering from nuclei and measurements of the form factors of bound nucleons.

The program proposed at the JLAB upgrade involves three processes: quasielastic (e,e'p) reactions on nuclei, ed→e'pn reactions in perpendicular kinematics and $ed \rightarrow e'd\rho^0$ reactions. The committee was told that carrying out these experiments would not be difficult.

A. The quasielastic (e,e'p) reaction is the simplest process. Previous measurements can be extended to Q^2=17 $(GeV/c)^2$. The effects of color transparency, manifested as a rise of the relative cross section as Q^2 increases, have been predicted using models consistent with the BNL (p,pp) experiment. The increase would be 20-30%, depending on the nucleus over the available range of Q^2. This is a simple reaction, but the predicted effects are not huge.

B. The quasielastic ^{2}H(e,e'p)n process (detecting the proton and neutron in perpendicular kinematics) offers the potential of large experimental signals of color transparency. Rescattering of the struck proton would lower the cross section for producing a final state in which the spectator neutron has a small (~200 MeV/c) momentum $p_\perp$, but it would greatly enhance the cross section in cases when the neutrons have higher $p_\perp$ (~400 MeV/c). At large values of Q^2, the effects of color transparency would severely suppress rescattering thus drastically changing the ratio of cross sections for large to small $p_\perp$. Large factors, 2 or more, are predicted. The interpretation does require that the momentum of the final neutron not be too large.

C. The process $ed \rightarrow e'd\rho^0$ requires more and more rescattering of the vector meson as the momentum transferred to the deuteron, |t|, increases from 0.4 to 0.8 $(GeV/c)^2$. At large values of Q^2 the effects of color transparency are predicted to suppress the rescattering. The predicted suppression factors are typically about a factor of 5.

The availability of 11-12 GeV electrons is absolutely necessary for each of the experiments put forth. These experiments offer the opportunity to definitively demonstrate or rule out the influence of color transparency effects for the physics of nuclei.

- **Possible Omissions in the program**

It is our conclusion that the community has done an excellent job in identifying the principal scientific issues that can be addressed with the JLAB 12 GeV upgrade. We would like to see further study in two areas, but we cannot immediately identify critical experiments that we are confident will lead to major progress.

1) Jefferson Lab is a world leader in using parity-violating electron scattering to study hadron and nuclear structure. A future experiment is under consideration to extract the weak charge of the proton. We would encourage further study in this sector of the electroweak interaction to determine if any new possibilities arise with the higher energy beams.

2) The nuclear dependence of deep inelastic scattering remains an important unsolved problem. The study of short-range correlation effects in the parton distributions at $x>1$ was identified above as an important research thrust. We see the possibility of other interesting new measurements of the nuclear EMC effect, both in inclusive and semi-inclusive scattering as the kinematic reach of the facility expands in the traditional scaling region. The recent HERMES measurements of the nuclear dependence of the ratio of longitudinal and transverse structure functions is one example of a measurement that could be well suited for the upgrade. Others are the use of hadron tagging of the flavor dependence of nuclear effects, the search for coincident correlated particles in the high-x region or the possibility of more complete determination of nuclear final states resulting from deep inelastic reactions.

Response to the Third Charge

3) Is the experimental equipment proposed well matched to the key physics experiments motivating the upgrade?

Hall A

The 12 GeV program in Hall A includes a variety of reactions that require in addition to the existing High Resolution Spectrometers, a spectrometer featuring higher momentum capability and larger solid angle, because of the high momentum of the reaction products and the low cross sections of the reactions of interest. The design of the proposed 6 GeV/c (maximum momentum) MAD spectrometer meets these requirements by using two identical dipole/quadrupole magnets with independently tunable superconducting coils.

The overall momentum and angle resolutions are sufficient for the reactions considered. The detector system was only indicated globally at this stage but the laboratory has considerable experience in this momentum range.

Hall B CLAS-Upgrade

A major issue for the CLAS is to provide more complete kinematic coverage to uniquely identify the final state. One important example is the study of deep exclusive scattering to probe the generalized parton distributions, with typical reactions like $ep \rightarrow e'pm$ in which the meson, *m,* and electron are produced with high energies in the forward direction (high W and Q^2, low t). As an example: γ and π^0 final states need to be distinguished. The CLAS detector has to be modified for that purpose. However, major parts will be kept. Since the reactions of interest have low multiplicity they need to be discriminated against high multiplicity backgrounds. This will be achieved by adding additional detector parts: a central detector (superconducting solenoid with tracker chamber and barrel calorimeter inside) to detect particles emitted at large angles ($\theta > 35^o$), and a segmented calorimeter (scintillators with short radiation length, choice of material and construction not yet decided) to cover the inside torus walls. In order to cover the forward angles ($\theta < 35^o$) with good resolution the present Region 1-3 chambers will be replaced by chambers with higher wire density and lower polar angle (θ) acceptance. In order to be able to distinguish between single photons (Compton) and the two decay photons from π^0 mesons (at minimum 10 cm apart at the forward calorimeter) a preradiator calorimeter will be added, with good spatial resolution at small θ.

There are still open questions that are being worked on. The concept is solid, the open questions will certainly be answered.

Hall A/C Electromagnetic calorimeter:

The instrument will serve to detect hard photons and needs to provide distinction between Compton photons and photons from π^0 decay to optimize the study of deep virtual Compton scattering. Therefore, it needs high granularity for good position resolution, and good energy resolution. Furthermore it needs to be fast and radiation hard (positioned in forward direction). The choice made is to use PbF_2 crystals (radiation length 0.98 cm, Cerenkov threshold for electrons ≈20 MeV) in an array of 1600 items, 3 by 3 by 15 cm^3, and 3.5 m from the target (for which there are existing examples). This will just be enough to detect the two photons from the highest energy π^0 meson decay separately (≈7 cm apart at the calorimeter). For pile-up and background reduction 1 GHz sampling ADC's and fast phototubes will be used for the crystal readout. The design is adapted to the problem, it cannot be built simpler and will fulfill the requirements.

Hall C SHMS Spectrometer:

The 12 GeV program in Hall C focuses on (e,e'x) coincidence reactions, where in addition to the scattered electron, which will have typical energies of up to about 7 GeV, a hadron x, which can have a large momentum, has to be detected in or close to the direction of the three-momentum transfer, **q**. Since the existing SOS spectrometer has too low maximum momentum and the most forward angle of the HMS spectrometer is only about 10 degrees, a new spectrometer, the Super High Momentum Spectrometer (SHMS), is proposed, which will accommodate momenta up to 11 GeV/c and (central) scattering angles as small as 5.5 degrees. These values are well matched to what is needed. Because of the forward angle capability the solid angle of the spectrometer will be relatively small, but since most reaction products of interest will be close to the direction of **q** this is not a major drawback. Also the aspect ratio with its larger vertical than horizontal acceptance alleviates the problem, since by taking data at more scattering angles the θ and φ dependence of the cross section around **q** can still be mapped out over a sizeable area.

The anticipated momentum and angle resolutions will yield missing mass resolutions of typically 20-30 MeV/c^2 when the 'struck' hadron is detected, which is more than sufficient. The angle resolution (and accuracy) is especially needed in structure function separations and in 'inverse detection' reactions like $^1H(e,e'p)\pi^0$. At the highest values of Q^2 the missing mass resolution in the latter reaction will be on the edge of what is needed and detailed simulations are required.

The wire chambers, scintillators and Pb-glass calorimeter of the detection system are standard and have proven their reliability.

With the higher hadron momenta involved, the particle identification techniques used in the HMS spectrometer are no longer sufficient. One possibility is to use an additional Cerenkov detector at low pressure, but other options like a transition radiation detector or aerogel, are being considered.

The laboratory needs to have one spectrometer that can cover the entire momentum range of the incident beam after the upgrade. The SHMS appears well suited to this need.

Summary

The Program Advisory Committee concludes that an outstanding scientific case has been identified which requires the unique capabilities of the JLAB 12 GeV upgrade. The results of these experiments are likely to significantly change the way we think about nuclear physics and the strong limit of quantum chromodynamics. Major thrusts to identify the properties of low lying QCD states beyond the well-known quark-antiquark states and to measure the single quark wave functions of the hadrons are expected to produce definitive results. If nature does not match our current expectations, the quality of the data will be such that our field will likely be forced to undergo a significant rethinking of strong QCD.

We find that this experimental program can be carried out with the Jefferson Lab upgrade. The proposed experimental equipment is well suited to the research program and appears to involve proven technological choices. While the major research thrusts are well served by these choices, in some instances, the initial program will be exploratory and concepts for new equipment will naturally evolve.

The PAC would like to acknowledge the major effort the user community and laboratory have devoted to coming to grips with the best science that can be addressed with electromagnetic probes in the 12 GeV regime and thoroughly exploring the physics alternatives. The few additions suggested by the PAC are more speculative in nature and involve legitimate open issues about their usefulness at this time.

Appendix 1

12 GeV Workshops in 2000

The user community has been studying the scientific potential of higher energy beams at Jefferson Lab for several years with major workshops in 1994 and 1998. Over the past year these efforts crystalized with a series of workshops to develop the scientific case for the upgrade that was presented to the Program Advisory Committee. A partial list of the workshops held this year is given below.

Physics Opportunities with 12-GeV Beams	January 13-15, 2000
Hadrons in the Nuclear Medium	March 7-10, 2000
Workshop on the Nucleon Structure in High x-Bjorken Region	March 30-April 1, 2000
Charm Studies at 12 GeV at JLab	April 3, 2000
Exclusive Reactions and Skewed Parton Distributions	April 13-15, 2000
Workshop on Quark-Hadron Transition in Structure And Fragmentation Functions	April 17-18, 2000
Exclusive Reactions and Skewed Parton Distributions	May 26, 2000
The Road to 12 GeV	June 21-23, 2000

Appendix 2

PAC 18 Membership

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Appendix 3

Agenda

Friday, July 14

8:00	Executive Session and Charge to Committee (L102/104)	
9:00	Welcome & Background (Auditorium)	C. Leeman
9:15	Science Driving the 12 GeV Upgrade (30 min)	N. Isgur
10:15	Coffee	
10:45	Detector for the 12 GeV Upgrade (30 min)	L. Cardman
11:45	A^n_1 for Valence Quarks (30 min)	Z-E. Meziani
2:45	Executive Session/Working Lunch	
1:45	d/u as x -> 1 (30 min)	M. Petratos
2:45	Coffee	
3:15	Deep Exclusive Scattering (45 min)	M. Guidal
4:45	Committee Executive Session (L102/104)	
6:30-7:30	Reception (Arc Auditorium)	

Saturday, July 15

8:00	Executive Session (L102/104)	
8:30	Duality (15 min)	C. Keppel
9:00	Short Range Correlations with DIS (15 min)	W. Boeglin
9:30	High Q2 few body form factors (15 min)	M. Petratos
10:00	Coffee	
10:30	F_{/pi} (15 min)	G. Huber

11:00	The Threshold /psi N Interaction (25 min)	E. Chudakov
11:45	Primakoff Production of \eta and \eta' (15 min)	L. Gan
12:15	Executive Session/Working Lunch	
1:15	Color Transparency (25 min)	R. Ent
2:00	Executive Session (L102/104)	

Note: The closeout for the 12 GeV reviews will be included in the normal PAC closeout 4:30 Wednesday afternoon.