

RESEARCH PERSPECTIVES AT JEFFERSON LAB*

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The plans for upgrading the CEBAF accelerator at Jefferson Lab to 12 GeV are presented. The research program supporting that upgrade is illustrated with a few selected examples. The instrumentation under design to carry out that research program is discussed.

1. Introduction

The design parameters of the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) were defined over two decades ago. Since then our understanding of the behaviour of strongly interacting matter has evolved significantly, providing important new classes of experimental questions which can be optimally addressed by a CEBAF-type accelerator at higher energy. The original design of the facility, coupled to developments in superconducting RF technology, makes it feasible to triple the initial design value of CEBAF's beam energy to 12 GeV in a cost-effective manner.

The research program with the 12 GeV upgrade will provide breakthroughs in two key areas: (1) mapping gluonic excitations of mesons and understanding the origin of quark confinement and (2) searches for physics beyond the Standard Model. The upgrade will also provide important advances in two additional areas: (3) a direct exploration of the quark-gluon structure of the nucleon and (4) the physics of nuclei to understand the QCD basis for the nucleon-nucleon force and how nucleons and mesons arise as an approximation to the underlying quark-gluon structure. An overview of the upgrade research program is given in its Conceptual Design Report¹.

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Lattice QCD calculations² have convincingly illustrated the linear quark-quark potential necessary for confinement. In a meson the quark and anti-quark are sources of color electric flux, which is trapped in a flux tube connecting the q and \bar{q} . However, very little is still known about the direct excitation of that flux tube. The observation of such direct manifestations of gluonic degrees of freedom will provide understanding of confinement³. The quantum numbers of the flux tube, added to those of a $q\bar{q}$ meson, can produce exotic hybrids with unique J^{PC} quantum numbers. These excitations can be probed far more effectively with photons than with π - or K-mesons, because the quark spins are aligned in the virtual vector-meson component of the photon. For a full partial-wave analysis of such excitations linearly polarized photons are a requisite. The Hall D research program will be focused on a definitive measurement of the spectrum of exotic hybrid mesons, expected in a mass range from 1 to 2.5 GeV/c².

One of the more compelling new opportunities with the 12 GeV upgrade will be a highly accurate measurement of the weak charge of the electron, via the parity-violating asymmetry in electron-electron (Møller) scattering. The achievable accuracy of such a measurement provides sensitivity to electron substructure to a scale of nearly 30 TeV. The measurement is also sensitive to the existence of new neutral gauge bosons in the range of 1 to 2 TeV; such model-dependent limits are comparable to those to be achieved by measurements at the Large Hadron Collider. Furthermore, the measurement will severely constrain the viability of SUSY models which violate R-parity. The upgraded beam energy will also make possible measurements of parity violation in deep inelastic scattering (PVDIS). On an isoscalar target at moderate x PVDIS is also sensitive to $\sin^2(\theta_W)$. A measurement of the PVDIS asymmetry will provide a very sensitive test of the electro-weak theory. Examples of additional PVDIS measurements are the value of $d(x)/u(x)$ as $x \rightarrow 1$, the search for evidence of charge symmetry violation at the partonic level, and the characterization of novel higher-twist effects. The PVDIS program will require the use of a new large-acceptance spectrometer/detector package.

A main focus of the research program will be the Generalized Parton Distributions (GPD) through the study of exclusive processes at large momentum transfer. The GPDs can be considered as overlap integrals between different components of the hadronic wave function⁴, governed by the selection of the final state. Measurements of these GPDs will thus make it possible to map out quark and gluon wave functions. The orbital angular momentum contribution to the nucleon spin can be directly accessed

through GPDs. Factorization is an essential ingredient in the extraction of GPDs. For Deeply Virtual Compton Scattering (DVCS) scaling will have been achieved at 11 GeV, but this has to be established experimentally for other processes.

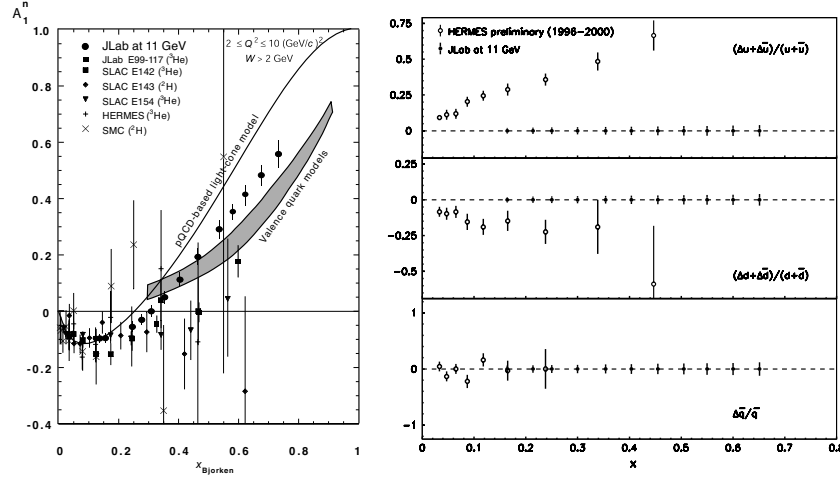


Figure 1. On the left is shown the projected measurement of A_1^n , on the right the projected determination of various combinations of polarized valence and sea quark distributions from semi-inclusive deep inelastic scattering.

One of the most fundamental properties of the nucleon is the structure of its quark distributions at higher x -values, where the physics of the valence quarks is cleanly exposed. The 12 GeV Upgrade will for the first time (by providing the necessary combination of high beam intensity and reach in Q^2) allow to map out the valence quark distributions at large x with high precision. Figure 1 (left) shows how the neutron polarization asymmetry A_1^n can be measured up to x -values close to 0.8 outside the nucleon resonance region. Most dynamical models predict that in the limit where a single valence up or down quark carries all of the nucleons momentum ($x \rightarrow 1$), it will also carry all of the spin polarization. Existing data on A_1^n show no sign of making the predicted dramatic transition $A_1^n \rightarrow 1$ (recent data from Hall A show the first hint of a possible upturn at the largest x -value).

There is a similar lack of data on other deep inelastic scattering observables in this region. One example is the ratio of down to up quarks in the proton, $d(x)/u(x)$, whose large- x behavior is intimately related to

the fact that the proton and neutron are the stable building blocks of nuclei. This ratio requires measurement of the neutron as well as the proton structure function. Information about the neutron has to be extracted from deuterium data, and is difficult to disentangle from nuclear effects at large x . Figure 2 shows the precision with which this fundamental ratio can be measured with the 12 GeV Upgrade. The proposed experiment will utilize a novel technique; detection of the slowly recoiling proton spectator will tag scattering events on a nearly on-shell neutron in a deuteron target. An independent measurement of $d(x)/u(x)$ can be made by exploiting the mirror symmetry of $A = 3$ nuclei in simultaneous measurements with ${}^3\text{He}$ and ${}^3\text{H}$ targets. Both methods are designed to largely eliminate the nuclear corrections, thereby permitting the d/u ratio to be extracted with unprecedented precision.

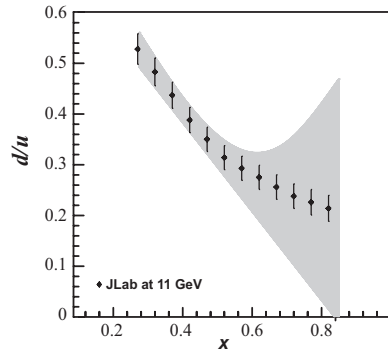


Figure 2. Projected measurement of the ratio of d - and u -quark momentum distributions, $d(x)/u(x)$, at large x . The shaded band represents the uncertainty in existing measurements due to nuclear Fermi motion effects.

The precise way in which the spin of the nucleon is distributed among its quark and gluon constituents is one of the most fundamental questions that can be addressed in nonperturbative QCD. Most of the experiments so far have focused on measuring the total quark and gluon contribution to the nucleon spin in inclusive deepinelastic scattering. In recent years the focus has moved to the investigation of specific aspects of the nucleon spin, such as the flavor asymmetries of sea quark distributions and quark transverse spin (transversity) distributions. The mapping of the flavor dependence of polarized valence and sea quark distributions and the determination of the quark transversity distributions require semi-inclusive measurements, in

which the detected final-state hadron reveals information about the spin, flavor, and charge of the struck quark participating in the deep-inelastic process. The 12 GeV Upgrade will provide a unique opportunity to perform semi-inclusive measurements with high precision over a wide kinematic range, producing a detailed picture of the spin structure of the nucleon. Figure 1 (right) shows how polarized valence and sea quark distributions can be extracted from semi-inclusive deep inelastic scattering by detecting the leading π^\pm and K^\pm hadrons.

At 12 GeV, the details of the nucleon-nucleon force can be probed at distance scales much less than the pion Compton wave length, where the effects of two-pion exchange, vector-meson exchange, and quark exchange all compete. Although well constrained phenomenologically by the large body of pp and np elastic scattering data, it is not yet understood under what circumstances the effective nuclear force can be described in terms of the exchange of mesons, and when it is more efficient to describe the force in terms of the underlying quark-gluon exchange forces. Alternatively, the atomic nucleus can be used as a laboratory to study how the underlying QCD non-Abelian degrees of freedom manifest themselves. The idea is here to strike a quark inside the nucleus with such velocity that one can uniquely witness how hadrons emerge on their path through the nucleus. Our present sketchy understanding of this process will be vastly improved with the 12-GeV program at JLab.

2. Accelerator

At present CEBAF accelerates electrons to 6 GeV by recirculating the beam four times through two superconducting linacs, each producing an energy gain of 600 MeV per pass. Both linac tunnels provide sufficient space to install five additional newly designed cryomodules. The new cryomodules will each provide over 100 MV (compared to the 28 MV from the existing ones), by increasing the gradient to 20 MV/m and the number of cavity cells from five to seven. This will result in a maximum energy gain per pass of 2.2 GeV, providing a maximum beam energy to Halls A, B and C of 11 GeV. The new Hall D will be provided with the desired maximum energy of 12 GeV by adding a tenth arc and recirculating the beam a fifth time through one linac. A total of 90 μA of CW beam can be provided at the maximum beam energy. Further modifications required are changing the dipoles in the arcs from C-type to H-type magnets, replacing a large number of power supplies and doubling the central helium liquifier capacity

to 10 kW. An overview of the accelerator upgrade is shown in Fig. 3.

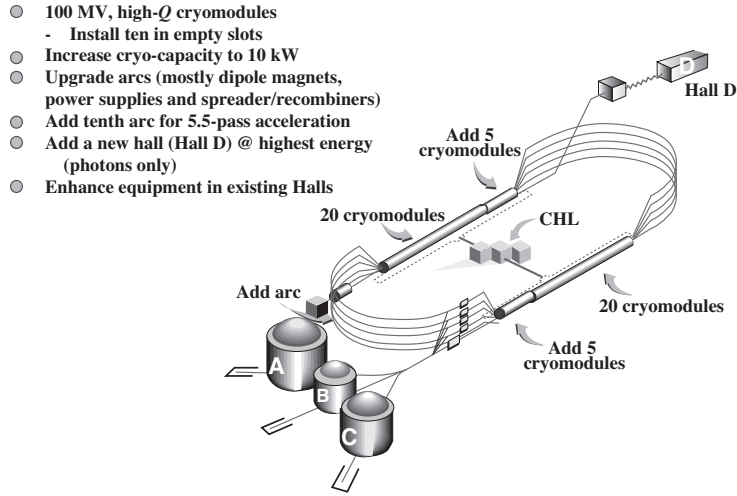


Figure 3. Overview of the accelerator upgrade to 12 GeV.

3. Hall Upgrades

The CEBAF Large Acceptance Spectrometer (CLAS) in Hall B is used for experiments that require the detection of several, loosely correlated particles in the hadronic final state at a limited luminosity. The CLAS12 detector has evolved from CLAS to meet the basic requirements for the study of the structure of nucleons and nuclei with the CEBAF 12 GeV upgrade. The main features are: 1) an operating luminosity of $L > 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ for hydrogen targets, a ten-fold increase over current CLAS operating conditions; 2) detection capabilities and particle identification for forward-going high momentum charged and neutral particles; 3) improved hermeticity for the detection of charged particles and photons in regions where CLAS currently has no detection capabilities. CLAS12 makes use of several existing detector components. Major new components include new superconducting torus coils that cover only the forward-angle range, a new gas Čerenkov counter for pion identification, additions to the electromagnetic calorimeters, and the central detector.

The Hall C facility has generally been used for experiments which re-

quire high luminosity at moderate resolution. The core spectrometers are the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS). The HMS has a maximum momentum of 7.6 GeV/c. At a 12-GeV Jefferson Lab, Hall C will provide a new magnetic spectrometer, the Super High Momentum Spectrometer (SHMS), powerful enough to analyze charged particles with momenta approaching that of the highest energy beam. Charged particles with such high momenta are boosted by relativistic kinematics into the forward detection hemisphere. Therefore, the SHMS is designed to achieve angles down to 5.5° , and up to 25° . The SHMS will cover a solid angle up to 4 msr, and boasts a large momentum and target acceptance. The magnetic spectrometer pair will be rigidly connected to a central pivot.

The present base instrumentation in Hall A has been used for experiments which require high luminosity and high resolution in momentum and/or angle of at least one of the reaction products. The central elements are the two High Resolution Spectrometers (HRS). Both of these devices provide a momentum resolution of better than 2×10^{-4} and an angular resolution of better than 1 mrad with a design maximum central momentum of 4 GeV/c. The beamline into Hall A will be upgraded so that the hall will be able to accept the full range of beam energies available for two major purposes. The first will be to continue the use of the high resolution spectrometer pair. The second purpose for Hall A will be to stage major installation experiments. With a diameter of over 50 m, Hall A is the largest experimental hall at Jefferson Lab and can easily accommodate major installations such as the proposed parity-violation setups.

3.1. *Hall D*

The GlueX experiment will be housed in a new aboveground experimental hall (Hall D) located at the east end of the CEBAF north linac. A collimated beam of linearly polarized photons (with 40% polarization) of energy 8.5 to 9 GeV, optimum for production of exotic hybrids in its expected mass range, will be produced via coherent bremsstrahlung with 12 GeV electrons. This requires thin diamond crystal radiators. The scattered electron from the bremsstrahlung will be tagged with sufficient precision to determine the photon energy to within 0.1%.

The GlueX detector uses an existing 2.25 T superconducting solenoid that is currently being refurbished. An existing 3000-element lead-glass electromagnetic calorimeter will be reconfigured to match the downstream

aperture of the solenoid. Inside the full length of the solenoid, a lead and scintillating fiber electromagnetic calorimeter will provide position and energy measurement for photons and TOF information for charged particles. A simple start counter will surround the 30 cm long liquid hydrogen target. This in turn will be surrounded by cylindrical straw-tube drift-chambers which will fill the region between the target and the cylindrical calorimeter. Planar drift chambers will be placed inside the solenoid downstream of the target to provide accurate track reconstruction for charged particles going in the forward direction.

This detector configuration has 4π hermeticity and momentum/energy and position information for charged particles and photons produced from incoming 9 GeV photons. It has been carefully optimized to carry out partial wave analysis of many-particle final states. The final planned photon flux is 10^8 photons/s. At this flux the experiment will accumulate in one year of running a factor of 100 more meson data than are presently available even from pion production.

4. Summary

In April of 2004 the US Department of Energy (DOE) signed CD-0 approval for the 12 GeV Upgrade project. With this Critical Decision #0 DOE acknowledges the mission need for this project. In April of 2005 the DOE Office of Science conducted a Science Review of the 12 GeV upgrade, which found the proposed research to have high scientific merit. Then, in July of 2005 DOE conducted a review of all aspects of the project's conceptual design. The review concluded that all of the requirements for CD- approval have been completed. Two further review processes in increasing level of detail, spaced 12 to 18 months apart, have to be successfully passed before funding for the project will be allocated.

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