Future Research Program at JLab: 12 GeV and Beyond

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Abstract

The project to upgrade the CEBAF accelerator at Jefferson Lab to 12 GeV is presented. Most of the research program supporting that upgrade, will require a highly polarized beam, as will be illustrated by a few selected examples. To carry out that research program will require an extensively upgraded instrumentation in two of the existing experimental halls and the addition of a fourth hall. The plans for a high-luminosity electron-ion collider are briefly discussed.

Key words: Electromagnetic processes and properties, Electroweak interactions, Polarized beams, Polarized and other targets

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1. Introduction

The original 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 significant 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

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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 Report[1].

Lattice QCD calculations[2] have convincingly illustrated the linear quark-quark potential necessary for confinement. The quark and anti-quark in a meson 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 confinement[3]. 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 GlueX research program will be focused on a definitive measurement of the spectrum of exotic hybrid mesons, expected in a mass range from 1.5 to 2.5 GeV/ c^2 .

Fig. 1. Projected measurements of PVDIS with the 12 GeV upgrade. On the left, the results are shown for the two electron-quark coupling constants C_{2q} , on the right those for 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.

One of the more compelling new opportunities with the 12 GeV upgrade, made possible by the unprecedented combination of high luminosity and parity quality of the beam, will be accurate measurements of parity violation in deep-inelastic scattering (PVDIS). At moderate x -values PVDIS off an isoscalar target is sensitive to the electron-quark coupling constants C_{2q} - see Fig. 1 (left) -, providing a sensitive test of electro-weak theory at the TeV scale. The PVDIS program will require the use of a new large-acceptance spectrometer, based on a large-volume and high-field solenoidal magnet. It will probe aspects of nucleon structure beyond the conventional quark-parton model, such as the onset of charge-symmetry violation and the size of higher-twist effects in the weak neutral current amplitude to very high precision. Accurate results on both these aspects

are required to reduce the systematic uncertainties in the results for C_{2q} . The PVDIS program will also provide precision measurements of the ratio $d(x)/u(x)$ as $x \rightarrow 1$, as shown in Fig. 1 (right), without any uncertainties from nuclear medium effects, since these measurements will be performed on a hydrogen target. The large-acceptance spectrometer can in addition be used for a broad program of exclusive and semi-inclusive reaction processes.

The upgraded beam energy will also make possible a highly accurate measurement of the weak charge of the electron, via the parity-violating asymmetry in electron-electron (Møller) scattering. The measurement would achieve the same level of precision as those of the weak mixing angle at electron-positron colliders on top of the Z resonance, thus possibly resolving the discrepancy of more than three standard deviations between the two most precise presently available results. 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 will be complementary to those to be achieved by measurements at the Large Hadron Collider. Furthermore, the measurement will severely constrain the viability of SUSY models that violate R-parity.

A main focus of the research program will be the Generalized Parton Distributions (GPD) through the study of a variety of exclusive processes at large momentum transfer in a broad kinematic domain. The GPDs can be considered as overlap integrals between different components of the hadronic wave function[4], 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 of the individual quark flavors 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 has been shown to be valid already at 6 GeV, but for other processes this has still to be established experimentally.

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. Most dynamical models predict that in the limit where a single valence up or down quark carries all of the momentum of the nucleon ($x \rightarrow 1$), it will also carry all of the spin polarization. Recent data from Hall A for the first time show a hint of a possible upturn in the neutron polarization asymmetry A_1^n at an x -value of ~ 0.6 . Figure 2 (left) shows how A_1^n can be measured up to x -values close to 0.8 outside the nucleon resonance region with the 12 GeV upgrade.

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 structure function of the neutron as well as of the proton. Information about the neutron has so far been extracted from inclusive deuterium data, where it is difficult to disentangle from nuclear effects at large x . 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 ^3He and ^3H

Fig. 2. 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.

targets. Both methods are designed to largely eliminate the nuclear corrections, thereby permitting the d/u ratio to be extracted with unprecedented precision.

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 deep-inelastic 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 2 (right) shows how polarized valence and sea quark distributions can be extracted from semi-inclusive deep inelastic scattering by detecting the leading $\pi^\pm$ 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.

The question whether a nucleon bound in the nuclear medium has different properties from those of a free nucleon, has been an issue in nuclear physics since the discovery of the EMC effect, over twenty years ago. The CW character of the CEBAF beam at 12 GeV opens a large window on measurements of structure functions in coincidence with spectator nucleons or target fragments. The CLAS12 detector with its large acceptance will allow reconstruction of the EMC effect from a complete measurement of the x -dependence of exclusive channels in a range of nuclei.

2. Accelerator

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

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 the existing 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 $90 \mu\text{A}$ 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 capacity of the central helium liquifier. An overview of the accelerator upgrade is shown in Fig. 3.

3. Existing Experimental Halls

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. 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 require 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, the SOS spectrometer will be replaced by 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 through the use of a small horizontal bend magnet to detect particles at angles down to 5.5° (and up to over 40°). The SHMS will cover a solid angle up to 5 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), to which recently a third spectrometer has been added with a large acceptance (BigBite). 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 three existing spectrometers. 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.

4. 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 the production of exotic hybrids in its expected mass range, will be produced via coherent bremsstrahlung

with 12 GeV electrons. This requires carefully aligned 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, originally built for the LASS spectrometer at SLAC, 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, an electromagnetic calorimeter utilizing scintillating fibers embedded in a lead matrix will provide position and energy measurement for photons and TOF information for charged particles. A fiber tracking device, doubling as a 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 10^7 photons/s. At this flux the experiment will accumulate already in one year of running a factor of 10 more meson data than are presently available even from pion production.

5. Electron-Ion Collider

Fig. 4. Overview of the proposed electron-ion collider.

At Jefferson Lab a plan for the next upgrade, involving an electron-ion collider (EIC) is already being developed. A Zeroth Order Design[5] has yielded a promising concept

for up to 225 GeV protons colliding with up to 9 GeV electrons (or positrons) at a luminosity of close to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$, thus at a center-of-mass energy of up to 81 GeV. Both electrons or positrons and protons, deuterons or ^3He ions would be circulating in two storage rings with four interaction regions at maximum polarization for either beam. Unpolarized ions up to mass ~ 200 would also be available. An overview of the proposed electron-ion collider is shown in Fig. 4.

6. Summary

In April of 2004 the US Department of Energy (DOE) signed CD-0 approval for the 12 GeV Upgrade project, acknowledging the mission need for this project. Then, in February of 2006 DOE approved the preliminary baseline range through the second Critical Decision. The first part of the CD-2 review has been successfully completed. The CD-3 review that would formally approve construction funds, is expected by the summer of 2008. The 12 GeV Upgrade project is the only large construction project underway at the Nuclear Physics program office in the DOE Office of Science. The present NSAC Long Range Plan has assigned the completion of the 12 GeV upgrade its highest priority. The present planning foresees an 11 GeV beam to be delivered to at least one hall and the start of the first experiments by late 2012, with full operations in all four halls to commence by 2015.

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