Physics Potential of the JLab Upgrade

J. P. Chen

Jefferson Lab
Newport News, VA 23606, USA

Abstract

The planned upgrade of the Jefferson Lab energy to 12 GeV will greatly expand the capability of the facility to make profound contributions to the study of nuclear and nucleon structure, and the strong interaction. In particular, it will allow direct exploration of the quark-gluon structure of hadrons and nuclei, and of quark confinement. The physics potential is illustrated with selected examples. The instrumentation under design to carry out the research program is also presented. The plan for an upgrade beyond 12 GeV is briefly discussed.

1 Introduction

The continuous electron beam accelerator facility (CEBAF) at Jefferson Lab (JLab) [1] was initially designed to accelerate electrons to 4 GeV. Currently, it can reach about 6 GeV due to excellent performance and improvement of the superconducting radio-frequency (SRF) accelerating cavities. CEBAF can deliver polarized electron beams up to 200 μA to three experimental halls for simultaneous electron scattering experiments. The experimental halls contain complementary base equipment to cover a broad physics programs. Hall A [2] has two high resolution spectrometers (HRS) for experiments requiring precise reconstruction of the unobserved hadron final state and is capable to reach a luminosity of 10^{39} particles/second. Hall B [3] is equipped with a large acceptance toroidal spectrometer (CEBAF Large Acceptance Spectrometer, CLAS) for the detection of multi-hadrons in the final state with luminosity capability of 10^{34} particles/second. Hall C [4] has two magnetic spectrometers: the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS) with the same luminosity capability as Hall A.

The current physics programs are focused mainly on 1) nucleon electromagnetic form factors, including strange form factors); 2) baryon resonances and their transition form factors; 3) nucleon spin structure functions; 4) structure and form factors of light nuclei and nuclear medium effects.

The 12 GeV energy upgrade [5] is cost-effective (at less than 30% of the cost of the original facility) and will allow breakthrough programs to be launched in following areas: 1) the experimental observation of the QCD flux tubes, which are related to the origin of the quark confinement; 2) the precise mapping of the valence quark longitudinal momentum and spin-flavor structure of the nucleon; 3) the exploration of the 3-dimensional structure of the nucleon by exploiting the generalized parton distributions. In addition, the upgrade will extend the current physics program to higher Q^2 to fully cover the transition into perturbative QCD region.

2 Gluonic Excitation: Search for Exotic Mesons

Lattice QCD calculations have demonstrated that the color string (or flux tube) concept, which was originally proposed by Nambu in the 1970s, is correct: in QCD, a string-like color-electric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see Fig. 1). In this picture, conventional mesons are a quark and an anti-quark connected by a flux tube in its ground state. It predicts the existence of mesons with an excited flux tube which exhibits explicit gluonic degree of freedom. These excited states (hybrid mesons) are predicted to have masses around 2 GeV and can have exotic quantum numbers which are forbidden for conventional mesons since the flux tube can independently posses angular momentum. Searching for mesons with exotic quantum numbers will provide definitive tests for the flux tube picture.

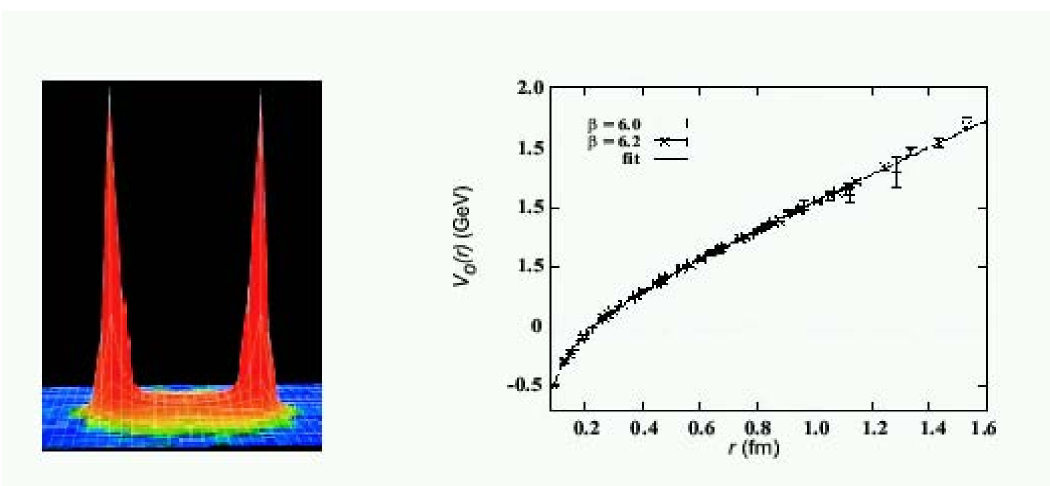

Fig. 1: A lattice QCD calculation of the energy density field between a quark and an anti-quark.

Photon beams are expected to be more favorable than pion or kaon beams for the production of the exotic hybrids, because the quark spins are aligned with the 'virtual vector meson' component of the photon. Linearly polarized photons are particularly useful for a full partial wave analysis. The optimal photon energy is about 9 GeV, which will be sufficient to access the mass range of 1 - 2.7 GeV, where the light hybrid mesons are expected to exist. Linearly polarized 9 GeV photons can be optimally produced by coherent bremsstrahlung with 12 GeV electrons.

3 Valence Quark Structure of the Nucleon

Deep inelastic scattering (DIS) experiments have provided us with an extensive data base on the structure functions and have enabled the extraction of the quark and gluon momentum distributions in the nucleon. The Q^2 evolution of the structure function is one of the few precise tests of QCD. Polarized DIS experiments have provided us with data on the spin structure functions and led to the conclusion that quarks only contribute about $20 - 30\%$ to the nucleon spin, the remaining comes from quark orbital angular momentum and gluon total angular momentum. These data have allowed the extraction of the quark spin distributions, but almost no information on the quark orbital angular momentum and the gluon total angular momentum exists. Due to the limited polarized luminosity, the polarized data base is much less extensive than the unpolarized one. In particular, there is practically no information on the neutron spin structure in the high x ($x > 0.4$) region, where the valence quarks dominate the wavefunction, which is a clean region to study the valence quark structure of the nucleon. The 12 GeV upgrade will open up a large kinematic region for DIS, and in combination with the high polarized luminosity, it will allow us to map out the quark momentum and spin-flavor distributions in this region with high precision.

The left panel of Fig.2 shows an example of a precision measurement of the neutron spin asymmetry A_1^n in the high x region. It will unambiguously establish the trend of A_1^n when x goes to 1, providing a benchmark test of pQCD and relativistic constituent quark models.

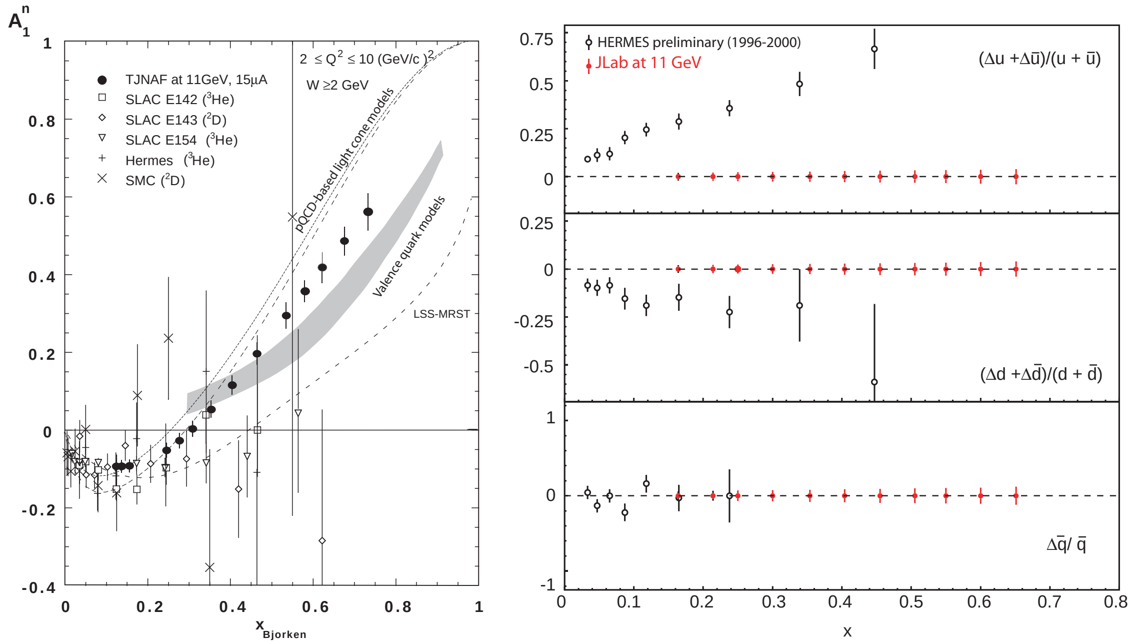

Fig. 2: A_1^n measurement and flavor decomposition from polarized semi-inclusive reaction.

The 12 GeV upgrade opens up a window for semi-inclusive DIS experiments. The validity of factorization will be experimentally tested. Polarized semi-inclusive meson production will allow a flavor decomposition of the quark spin distributions. The right panel of Fig. 2 shows an example of the precision and range of observation that can be achieved in flavor decomposition of polarized quark distributions using semi-inclusive π^+ and π^- production with a polarized beam on polarized proton and neutron targets.

Even the unpolarized structure is not fully understood in the high x region. The d/u ratio has been an outstanding issue for years, mostly due to the uncertainty in the extraction the F_2^n from the deuteron measurement. JLab will be able to measure, with high precision, the d/u ratio with two different methods: using the super ratio of the ^3H to ^3He structure functions and by tagging the neutron with detection of the backward-scattered proton in the deuteron.

The upgrade will allow a precise map of the g_1 and g_2 structure functions for a wide Q^2 and x region, in particular, the d_2 matrix element, allowing a benchmark test of lattice QCD.

4 A Three-Dimensional View of the Nucleon

The framework of the Generalized Parton Distributions (GPD's) has made it possible, in principle, to map out the complete quark-gluon wavefunctions of the nucleon, therefore providing a 3-dimensional view of the nucleon. The framework links many processes together: quark longitudinal momentum distributions, quark spin distributions, form factors, quark orbital angular momentum, quark transverse momentum distributions, and pion distributional amplitudes. The GDP's can be extracted through exclusive processes: deep virtual Compton scattering (DVCS) or deep virtual meson productions (DVMP) (see Fig. 3).

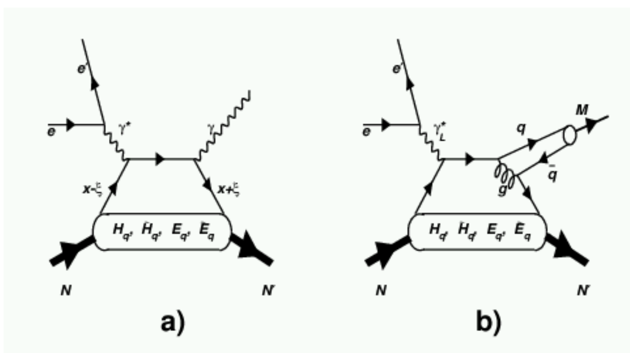

Fig. 3: The GPDs can be extracted through a) DVCS, and b) DVMP.

The 12 GeV upgrade opens up a wide window for deep exclusive measurements. An example of a projected DVCS measurement with upgraded CLAS (CLAS++) is shown in Fig. 4.

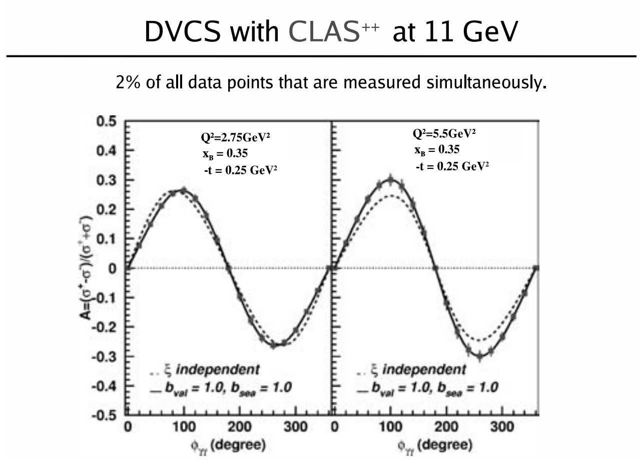

Fig. 4: A projected DVCS measurement with CLAS++.

5 Expanding the Current Research Programs

The current research programs at JLab will be greatly extended to higher Q^2 and higher energy. Following are some of the new opportunities the upgrade will bring to us: 1) Extending the measurements of hadron form factors to high Q^2 to determine the dynamics underlying the quark-gluon wavefunctions. An example of the measurement of the pion form factors is shown in Fig. 5. 2) Mapping out and understanding the transition from the hadronic to the quark-gluonic description of strongly interacting matter through the study of quark-hadron duality and photon-production experiments. 3) Searching for the onset of color transparency effects in the region where they are expected to exist. 4) Study short-range-correlations in nuclei and probe the limits of the standard model of nuclear physics by exploring the low-temperature, high density phase. 5) Determine the role of color polarization effects in the NN force by measuring the threshold ΨN cross sections.

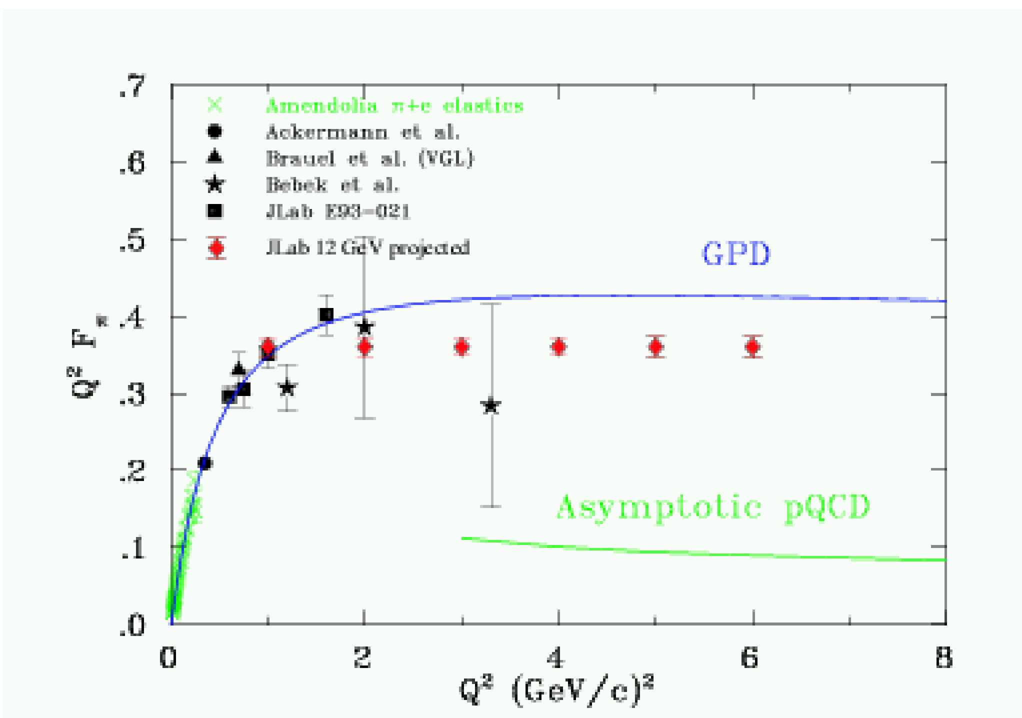

Fig. 5: Projected pion form factor F_π measurement.

6 Facility Upgrade

The current electron accelerator at JLab consists of 40 SRF accelerating cryomodules. Their performance has exceeded the design goal significantly, which has made it possible to reach 6 GeV energy (150% of the initial design energy of 4 GeV) while there is still un-used space remaining in the linac for an additional 10 cryomodules. The SRF technology has had further improvements over the last decade. With a new compact design of the cryomodules, it is possible to upgrade the CEBAF energy to 12 GeV at only a modest cost.

The maximum energy of 12 GeV will be available for Hall D [6], a new experimental area devoted to the search of exotic mesons using a linearly polarized photon beam and a large acceptance detector (GlueX). Energy up to 11 GeV will be available for the three existing halls. The existing equipment in the three halls will be upgraded to make full use of the higher energy. A broad range spectrometer (Medium Acceptance Detector, MAD) will be added in Hall A [7]. The CLAS in Hall B will be upgraded [8] to accept higher luminosity of 10^{35} particles/second with improved forward angle coverage. In Hall C, a new Super High Momentum Spectrometer (SHMS) [9] will be added to cover high momentum and forward angles.

The JLab 12 GeV upgrade has been endorsed by the National Science Advisory Committee and has been placed on the near-term priority list of the DOE 20-year projects [10].

7 Beyond 12 GeV

For the long term plan beyond the 12 GeV upgrade, a conceptual design has been developed at JLab for a high luminosity asymmetric electron-light-ion collider (ELIC) [11]. The electron energy will be around 5 (3-7) GeV and the ion energy will be around 50 (30-150) GeV. Luminosity of the ELIC can reach up to 10^{35} particles/second. This design will also provide a 25 GeV electron beam for fixed-target experiments. ELIC will allow a full investigation of the quark-gluon structure of the nucleon and nuclei through inclusive and semi-inclusive DIS, and exclusive reactions in a wide kinematic region, especially the low x region. It will provide answer to the questions of how quarks and gluons provide the binding and spin of the nucleons and nuclei, and how they evolve into hadrons.

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References

[1] http://www.jlab.org/

[2] http://hallaweb.jlab.org/

[3] http://clasweb.jlab.org/

[4] http://www.jlab.org/Hall-C/

[5] White Paper: The Science Driving the 12 GeV Upgrade of CEBAF (2001); pCDR for the 12 GeV Upgrade Science and Equipment (2003) http://www.jlab.org/div_dept/physics_division/GeV.html

[6] The GlueX/Hall D Design Report (2003); http://www.gluex.org/.

[7] The Hall A Preconceptual Design Report (2003); http://hallaweb.jlab.org/12gev.

[8] The Hall B Preconceptual Design Report (2003); http://clasweb.jlab.org/12gev.

[9] The Hall C Preconceptual Design Report (2003); http://www.jlab.org/Hall-C/upgrade.

[10] Facilities for the Future of Science: A Twenty-Year Outlook, DOE (2003).

[11] L. Merminga, *et al.*, Proceedings of EPAC 2002, Paris (2002).