THE UPGRADE OF CEBAF TO 12 GEV: PHYSICS MOTIVATIONS AND TECHNICAL ASPECTS

B. A. MECKING AND L. S. CARDMAN
Physics Division, Thomas Jefferson National Accelerator Facility,
12000 Jefferson Avenue, Newport News, Virginia 23606, U.S.A.
E-mail: mecking@jlab.org, cardman@jlab.org

The Continuous Electron Beam Accelerator Facility, CEBAF, makes use of electron and photon beams with an energy up to 6 GeV to investigate the electromagnetic structure of mesons, nucleons, and nuclei. We discuss the physics motivation for upgrading the facility to a maximum energy of 12 GeV and some of the key technical aspects of the upgrade.

1. Introduction

There are important physics questions that cannot be addressed now due to the lack of an electron accelerator with the combination of high energy, duty-cycle, and beam power required to study rare phenomena. Of particular importance are:

- clarifying the origin of quark confinement by searching for $q\bar{q}$ systems with excited flux tubes
- determining the longitudinal momentum distribution of the valence quarks in the nucleon via deep-inelastic inclusive scattering
- measuring quark–quark correlations via exclusive processes (by exploiting the recently developed formalism of the Generalized Parton Distributions).

To address these issues, plans have been developed for increasing the energy of the CEBAF accelerator to 12 GeV, and upgrading the experimental equipment to provide capabilities matched to the higher beam energy. These plans have been endorsed by the Nuclear Science Advisory Committee, NSAC.

2. The Status of CEBAF Today

The Southeastern Universities Research Association (SURA), a university consortium, operates the Thomas Jefferson National Accelerator Facility, also called Jefferson Lab (or JLab), for the U.S. Department of Energy. The main research instrument at JLab is the Continuous Electron Beam Accelerator Facility, CEBAF, a superconducting electron accelerator capable of delivering three electron beams with independent currents and independent, but correlated energies for simultaneous experiments in three halls, labeled Halls A, B, and C. The beam has a maximum energy of 5.8 GeV, a maximum power of 1 MW, and 100% duty-cycle. The halls contain complementary equipment to cover a wide range of physics problems. Hall A has two high resolution magnetic spectrometers for experiments that require the precise reconstruction of the mass of an unobserved hadronic final state. Hall B is equipped with a toroidal multi-gap spectrometer (the CEBAF Large Acceptance Spectrometer, CLAS) for the detection of several loosely correlated particles in the hadronic final state. Hall C includes two general-purpose magnetic spectrometers: the High Momentum Spectrometer (HMS) and the Short Orbit Spectrometer (SOS), as well as the infrastructure and space for mounting a variety of specialized experiments. Examples of recent experiments that also serve to highlight the capabilities of the accelerator and the present equipment in the halls are: the measurement of the ratio of the electric and magnetic form factors of the proton [1], the study of the strange quark content of the nucleon via parity violation in elastic $\vec{e}-p$ scattering [2], the separation of the three form factors of the deuteron via combining the tensor polarization of the recoiling deuteron in elastic $e-d$ scattering with the existing unpolarized measurements [3], and the measurement of the quadrupole strength in the $N \to \Delta$ transition [4,5].

3. The Physics of CEBAF at 12 GeV

The physics motivation for the 12 GeV upgrade has been described in detail in a White Paper [6]. Some important examples presented in that document are discussed in the following sections.

3.1. *Spectroscopy of Gluonic Excitations*

Exploratory numerical solutions of QCD ("lattice QCD") for distant static heavy quarks suggest [7] that confinement is caused by the formation of a string-like chromoelectric flux tube. Models for light quarks [8] predict that

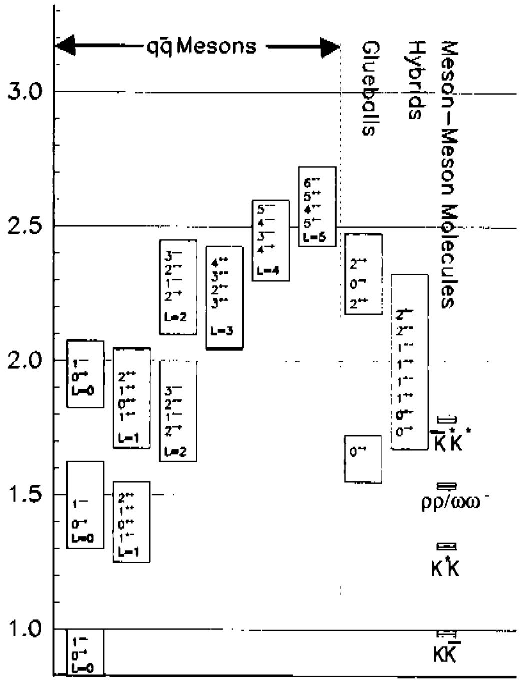

Figure 1. Level diagram showing masses (in GeV) of the conventional meson nonets and of expected glueballs and hybrids; also shown are the thresholds for molecular (2-meson) states. L refers to the angular momentum between the quarks, and each J^{PC} refers to a nonet of mesons.

a new form of hadronic matter exists in the mass region around 2 GeV in which the gluonic degree-of-freedom of a quark-antiquark system is excited. For some of these new states the vibrational quantum numbers of the flux tube, when added to those of the quarks, produce J^{PC} combinations not allowed for ordinary $q\bar{q}$ states. These unusual states (such as 0^{+-}, 1^{-+}, and 2^{+-}) are called *exotic hybrid mesons* [9]. Their masses, orderings, and decay mechanisms will provide experimental information on the mechanism that produces the flux tube.

Figure 1 shows a level diagram giving the range of masses for the conventional $q\bar{q}$ nonets, estimates of the masses of the lightest glueballs and hybrids, and thresholds for possible "molecular" meson-meson bound states.

Most of the searches for exotic mesons have been conducted with pion beams. The disadvantage of that approach is that the production of exotic combinations is suppressed because the spins of the quarks in the probe are antiparallel ($S = 0$) while the spins of the quarks in the exotic hybrid states are parallel ($S = 1$). In contrast, a photon can easily fluctuate into a vector meson with parallel quark spins. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic J^{PC} are possible. This makes photon beams particularly suitable for the production of exotic hybrids [8].

Experimental prerequisites to search for exotic hybrids in the 1.5 to 3 GeV mass region are a high-flux beam of linearly polarized photons with an energy of about 9 GeV, and a large acceptance detector with hermetic coverage for multi-particle final states to facilitate the extraction of exotic waves via a partial-wave analysis.

3.2. *Momentum Distributions of the Valence Quarks*

Deep inelastic scattering (DIS) experiments have led to the experimental confirmation of the existence of quarks, and to precision tests of QCD. However, there has never been an experimental facility with sufficient luminosity to measure DIS cross sections in the kinematic regime where the three basic ("valence") quarks of the proton and neutron dominate the wave function, i.e. for values of Bjorken-$x \to 1.0$. The 12 GeV upgrade will allow us to map out the quark distribution functions in this region with high precision.

Figure 2 shows one example of a measurement that is particularly well suited for the upgrade. The neutron polarization asymmetry A_1^n is sensitive to the spin wave function of the quarks. Most dynamical models predict that in the limit where a single quark carries all of the nucleon's momentum, it will also carry all of the spin polarization ($A_1^n \to 1$ as $x \to 1$). Existing data on A_1^n end before reaching the region of valence quark dominance, and show no sign of making the predicted transition $A_1^n \to 1$.

Even in unpolarized DIS, where the available data are best, there are unresolved issues. To extract the ratio of the probability of finding a d quark vs. a u quark at high x requires combining proton and neutron measurements. However, high-x neutron information is difficult to disentangle from nuclear binding corrections. To overcome this problem a planned experiment will exploit the mirror symmetry of $A = 3$ nuclei through simultaneous measurements of the inclusive structure functions for ^{3}H and ^{3}He. In this case the differences in the nuclear corrections is estimated to be quite small, permitting the neutron-to-proton ratio (and thus the d/u ratio) to be extracted with precision.

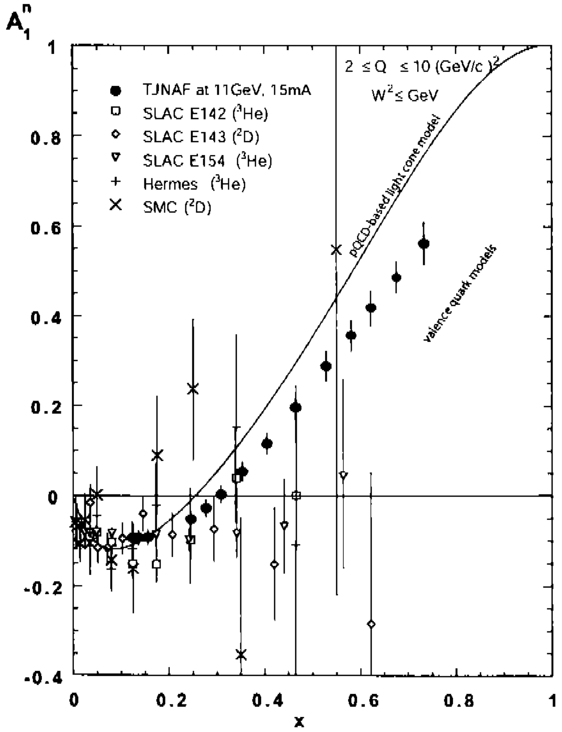

Figure 2. A projected 12 GeV measurement of the neutron polarization asymmetry A_1^n. The shaded band represents the range of predictions of valence quark models; the solid line is the prediction of a pQCD light-cone quark model.

3.3. *Quark-Quark Correlations from Deep Exclusive Scattering*

The information that can be obtained in DIS is limited to the square of the quark momentum wave function along the direction of the virtual photon (i.e. averaged over momenta transverse to the virtual photon direction). The new insights provided by the discovery of the Generalized Parton Distributions (GPD's) has made it possible, in principle, to map out the complete wave functions [11,12]. The GPD's are sensitive to the wave function at the amplitude level, instead of merely at the probability level, and, in particular, allow one to explore quark-quark correlations. The GPD's can be extracted from the cross sections for deep exclusive scattering (DES) processes with either a photon (Deeply Virtual Compton Scattering, DVCS)

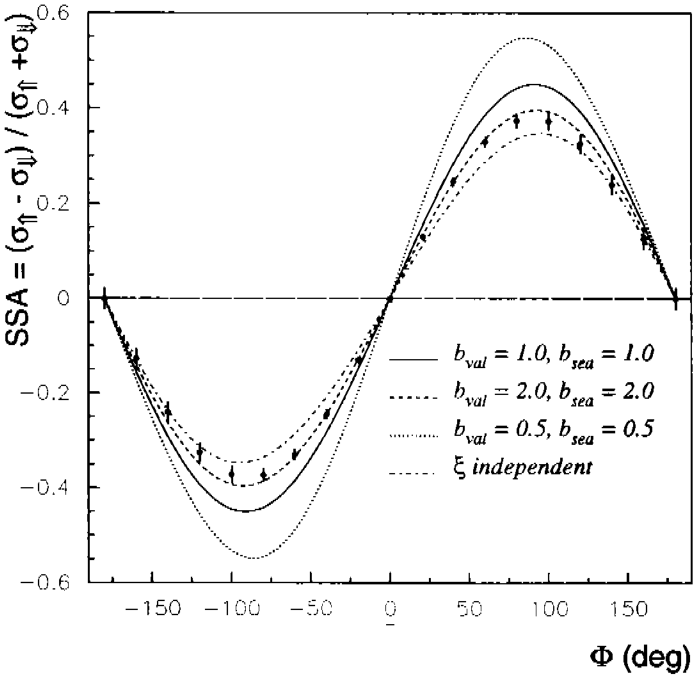

Figure 3. A projected measurement of the single-spin asymmetry for $\vec{e}p \to ep\gamma$ with longitudinally polarized 11 GeV electrons. Bins of $Q^2 = (3 \pm 0.1)$ (GeV/c)^2, $W = (2.8 \pm 0.15)$ GeV, and $-t = (0.3 \pm 0.1)$ (GeV/c)^2 were used. The curves indicate various GPD models, all of which are compatible with the known longitudinal parton momentum distributions.

or a meson in the final state. These processes access a rich body of new information about the full wave function, including non-forward overlaps of their longitudinal parts and their transverse momentum structure.

The necessary condition for the applicability of the GPD formalism is that the underlying processes can be factorized into a "hard" pQCD scattering amplitude and a "soft" amplitude that arises from the quark wave functions. The kinematic range over which measurements must be done to ensure that DES scaling (and thus factorization) holds must be determined experimentally.

The 12 GeV upgrade will allow DES cross sections to be investigated in the relevant kinematic regions for the first time. Scaling is expected to be reached early in the accessible regime in the case of DVCS. However, for deep virtual meson production, an additional hard collision is required;

this will likely shift the onset of scaling to higher momentum transfers. One may, therefore, expect that either scaling will be achieved in these processes, or that the scaling limits can be inferred from the behavior of the measured cross sections.

The upgraded large acceptance detector CLAS in Hall B will cover both DVCS and meson production processes at a luminosity of $L = 10^{35}$ cm^{-2} s^{-1}. For DVCS, the interference with the Bethe-Heitler process leads to a single-spin asymmetry. Figure 3 shows the projected data for this quantity at $Q^2 = 3$ (GeV/c)^2 for a 500 hour run with CLAS.

3.4. *Form Factors at High Q^2*

The high-Q^2 behavior of elastic and transition form factors probes the high-momentum components of the valence quark wave functions. It is of particular interest to understand where the dynamics of the valence quarks makes a transition from the "strong" QCD of confinement to the "weak" perturbative QCD applicable at very high energies and short distance scales. This transition should occur first in the simplest systems; in particular, the pion elastic form factor seems the best prospect for observing this transition experimentally. An experiment planned for Hall C will push the measurement of the pion form factor to $Q^2 = 6$ (GeV/c)^2. Projected data are displayed in Fig. 4.

4. Technical Aspects of the Energy Upgrade

The optimization of the physics reach, in combination with practical considerations, has led to the selection of 12 GeV as the maximum energy for the upgrade proposal [6]. A maximum energy higher than 12 GeV would make it possible to reach higher momentum transfer, Q^2, and thus make covering the deep-inelastic regime easier. However, with increasing energy the requirements on detector resolution and luminosity (to get sufficient count rate at the higher Q^2) will become increasingly difficult and costly to meet, and the cost of the accelerator upgrade will rise sharply above 11 GeV delivery to the present end stations (and above 12 GeV to the proposed new experimental hall).

The 12 GeV upgrade will require increasing the energy gain available from a single traversal of the linear accelerator pair from the present 1.2 GeV to 2.2 GeV; this will be accomplished by installing additional accelerating structures. All of the recirculating arcs will have to be upgraded to higher integral magnetic field. The highest energy of 12 GeV will be avail-

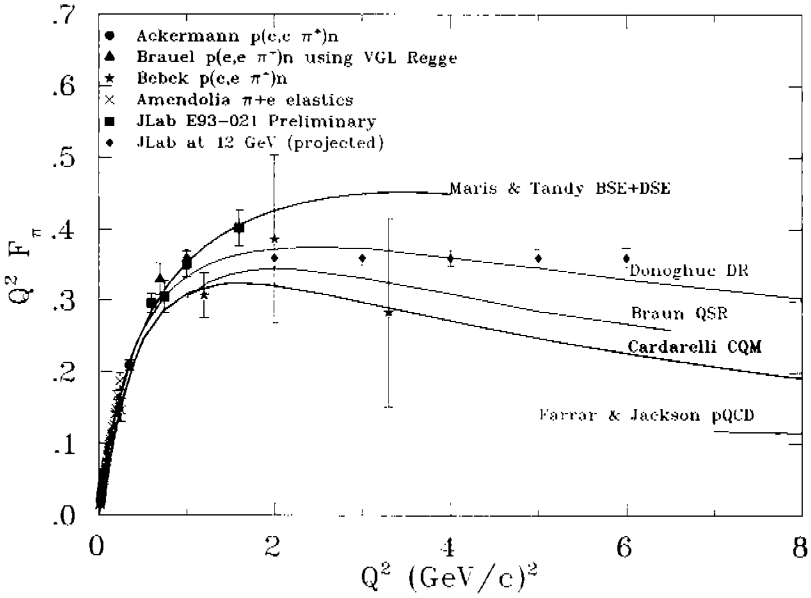

Figure 4. Projected data points (diamonds) for the pion form factor extracted from the measurement of the $ep \to e\pi^+(n)$ reaction with an 11 GeV electron beam in Hall C.

able in a new experimental area at the end of the north linac, Hall D. This area will be devoted to the photoproduction of exotic mesons using a 9 GeV linearly polarized photon beam (produced using 12 GeV electrons and the coherent bremsstrahlung technique) and a large acceptance solenoidal detector. The three existing areas will be able to use any multiple of 2.2 GeV (or a lower energy), up to 11 GeV. The layout of the facility is shown in Fig. 5.

The equipment in the present halls will be upgraded to take advantage of the higher energy. In Hall A, a broad-range spectrometer (Medium Acceptance Detector, MAD) will be added. The CLAS in Hall B will be upgraded to higher luminosity ($L = 10^{35}$ cm^{-2}s^{-1}) and improved forward coverage. In Hall C, the SOS will be replaced by a new Super High Momentum Spectrometer, SHMS, to cover small angles and high momenta.

5. Long-Range Possibilities

Looking to possibilities beyond the 12 GeV upgrade, the JLab accelerator team has started to investigate the beam dynamics and technical issues

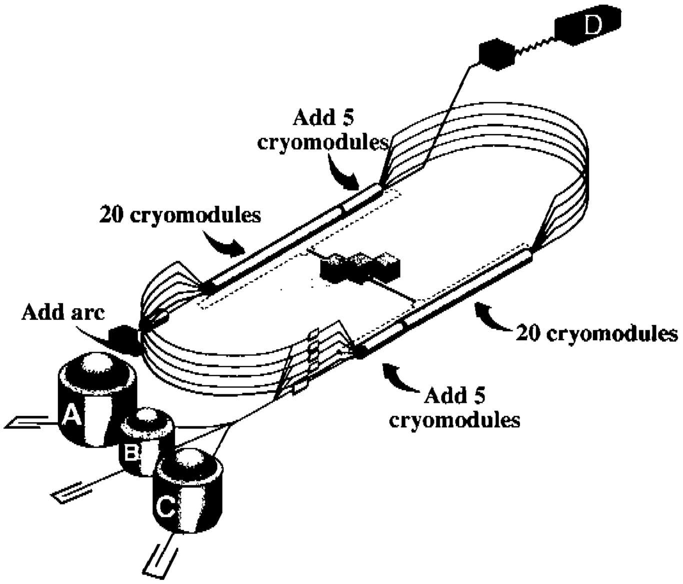

Figure 5. Layout of the 12 GeV upgrade of CEBAF

associated with an electron-light ion collider. The energy range that has been considered is (3-5) GeV electrons colliding with (30-50) GeV light ions. Such a facility, with adequate luminosity, would permit extending DES studies of the nucleons to much lower values of Bjorken-x, permitting the study of the sea quarks as well as the valence quarks accessible via the 12 GeV upgrade.

Preliminary studies show a maximum luminosity of 6×10^{34} cm^{-2}s^{-1} can be reached by colliding an electron beam out of a linear accelerator with light ions circulating in a ring (linac-ring collider). This requires recovering the energy contained in the electron beam, a technique which has been pioneered at high beam intensities by the JLab infra-red Free Electron Laser. Electron beam cooling will be necessary to reduce the emittance of the light ion beam. It should be pointed out that a major R&D effort will be required to solve the technical difficulties associated with the challenging beam parameters for the collider. An interesting side benefit of this approach to a collider is that a high intensity, 25 GeV external electron beam could be generated by recirculating the beam five times through the 5 GeV linac pair (as in the present accelerator), permitting high-luminosity ($L \approx 10^{38}$ cm^{-2}s^{-1}) fixed-target experiments.

6. Summary

The physics motivation for the proposed 12 GeV upgrade of the Continuous Electron Beam Accelerator at JLab has been discussed. The unique combination of high energy, high duty-cycle, high intensity and small phase space beams from CEBAF's superconducting accelerator, in combination with complementary equipment in four experimental halls, will make it possible to perform experiments that will determine the internal structure of mesons, nucleons, and nuclei with unprecedented precision.

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