From Quarks to Nucleons
Highlights from the Research Program in Hall A at JLab

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Abstract

After a brief introduction to the CEBAF accelerator, several recent results of the research program in Hall A are discussed. All of these address the transition region between the meson-baryon and quark-gluon description of nuclear matter. Finally, the plans for upgrading CEBAF to 12 GeV are presented and the instrumentation under design for Hall A to carry out that research program is discussed.

1. Introduction

One of the main motivations for building the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLab) was the investigation of the fundamental structure of nuclear matter. It has been established that at large-distance scales nuclei are well described in a meson-baryon model, while at short-distance scales the coupling between nucleons involves elementary quark and gluon fields. Very little is known, however, how and when the transition from one description evolves into the other. It is especially on this transition region that many of the experiments at CEBAF are focussed.

Our understanding of the behaviour of strongly interacting matter has evolved significantly since the original conception of CEBAF, providing important classes of experimental questions which can be optimally adressed by a CEBAF-type accelerator at higher energy. Fortunately, foresight in the design of the facility, coupled to technical developments, makes it feasible to triple the initial design value of CEBAF's beam energy to 12 GeV in a very cost-effective manner.

2. Accelerator

CEBAF was designed to accelerate electrons to 4 GeV by recirculating the beam four times through two superconducting linacs, each producing an energy gain of 400 MeV per pass. Beam can be injected into the accelerator from either a thermionic or one of two polarized guns. In the polarized gun a strained GaAs cathode, illuminated by a 1497 MHz gain-switched diode or Ti-Sapphire laser, produces a beam polarization in excess of 70% at a current of well over 100 μA. Each linac contains 20 cryomodules with a design accelerating gradient of 5 MV/m. Ongoing *in situ* processing has already resulted in an average gradient in excess of 7 MV/m, which has made it possible to accelerate electrons to 5.7 GeV. The total maximum current is 200 μA CW, which can be split arbitrarily between three interleaved 499 MHz bunch trains. One such bunch train can be peeled off to any one of the three experimental Halls after each linac pass using RF separators and septa, while all Halls can simultaneously receive the maximum energy beam. Hall B with its large-acceptance detector CLAS requires a current as low as 1 nA, while a 100 μA beam is being delivered to one or even both of the other Halls.

3. Hall A

The base instrumentation in Hall A [1] has been used with great success 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 have proven to 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.

3.1. *The proton charge form factor*

Until recently the proton electro-magnetic form factors were measured by a Rosenbluth separation. For the charge form factor this method resulted in significant systematic errors, especially at larger Q^2-values. The measurement of the transverse and longitudinal recoil polarization in the $\vec{e}p \rightarrow e\vec{p}$ reaction provides an alternative method to measure the ratio $\mu_p G_E^p/G_M^p$ with excellent control of the systematic errors. The results of the first such measurement up to a Q^2-value of 3.6 GeV^2 [2] have shown (Fig. 1) that the proton charge form factor deviates significantly from its magnetic form factor. A dimensional-scaling pQCD model predicts the ratio $Q^2F_2^p/F_1^p$ to reach a constant value at large Q^2. The present data have not yet reached such a plateau at 3.6 GeV^2, but a recent study of Ralston et al. [3] predicts rather QF_2^p/F_1^p to scale, a behavior which is supported by the present data.

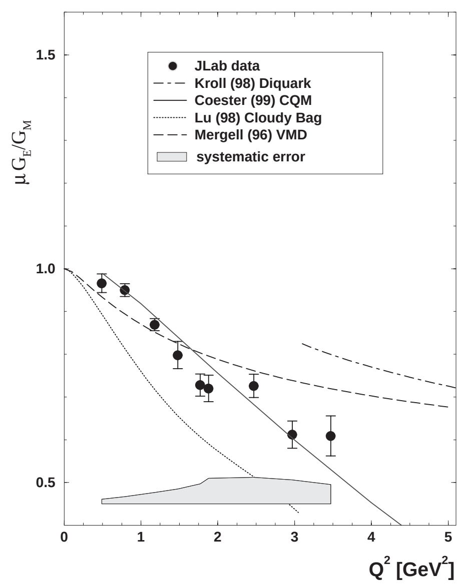

Fig. 1. The ratio $\mu_p G_E^p/G_M^p$ measured with the recoil-polarization method, compared with some recent calculations. The systematic error is indicated by the shaded area.

3.2. *Deuteron structure functions*

Measurements of the deuteron elastic form factors provide sensitive tests of the short-range nucleon-nucleon interaction, meson-exchange currents and explicit quark degrees of freedom. The deuteron electric form factor $A(Q^2)$ has been measured up to $Q^2 \approx 6$ GeV^2 [4]. Essential to measuring a cross section as low as 10^{-41} cm^2/sr was a luminosity of $\approx 10^{38}$ cm^{-2}/s (120 μA on a 15 cm long LD_2 target) and the coincident detection of the scattered electron and the recoiling deuteron. The results (Fig. 2) are well described by relativistic meson-baryon calculations [6,7,8], in which the major uncertainty is the Q^2-dependence of the $\rho\pi\gamma$ meson-exchange correction. On the other hand, the data also follow the asymptotic pQCD prediction of Brodsky et al.[9]

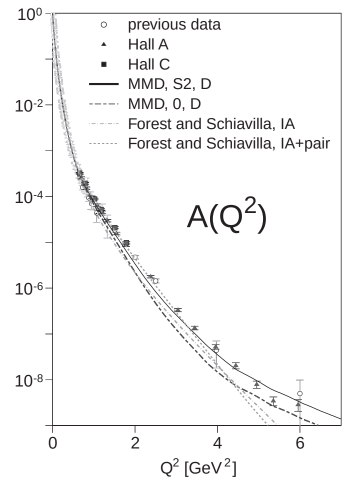

Fig. 2. The deuteron elastic form factor $A(Q^2)$ compared to meson-baryon calculations. Also shown are data from Hall C [6] and previous SLAC data.

3.3. Deuteron photo-disintegration

Recent measurements [10] of deuteron photo-disintegration show that the cross section at θ_{CM} = 90° follows an s^{-11} scaling behaviour at the highest energies, consistent both with a meson-baryon calculation and with pQCD. In Hall A the recoil-proton polarization was measured with a circularly polarized bremsstrahlung beam, to provide a better discrimination between the various models. The results [11] show (Fig. 3) that the induced polarization P_y vanishes above 1 GeV, at variance with a meson-baryon calculation. The vanishing of P_y is naturally explained by hadron helicity conservation within pQCD. On the other hand, the observed non-zero value of the polarization-transfer observable in the same energy region is in disagreement with HHC.

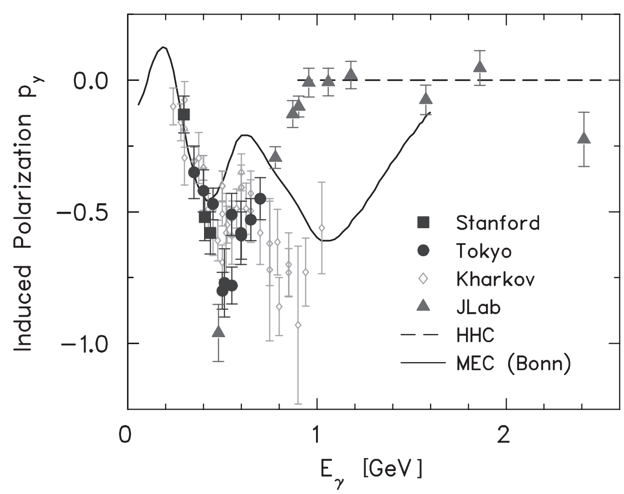

Fig. 3. The induced polarization P_y in the $\vec{\gamma}d \rightarrow \vec{p}n$ reaction at $\theta_{CM} = 90°$.

3.4. The Q^2-evolution of the GDH sum

The spin structure of the nucleon offers a unique opportunity to study the evolution of QCD from the low-Q^2 limit of confinement to the perturbative regime of asymptotic freedom, from the Gerasimov-Drell-Hearn sum rule to the Bjørken sum rule. The Q^2-evolution of the generalized GDH sum rule for the neutron was studied [12] in the range of 0.1 to 1.0 GeV^2 by measuring quasi-elastic scattering of polarized electrons from a spin-exchange polarized ^{3}He target. Figure 4 shows preliminary results from this experiment, where the experimental GDH sum on ^{3}He has been corrected [13] for the nuclear medium to provide results for the neutron.

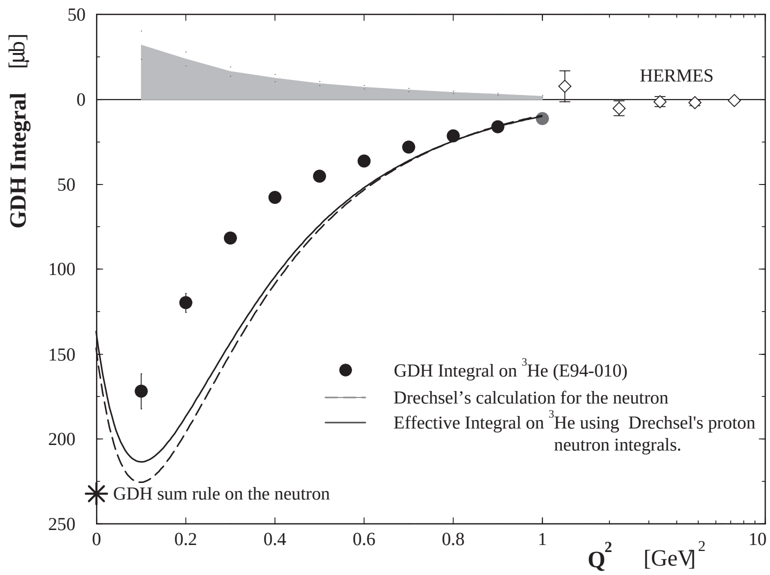

Fig. 4. Preliminary data for the GDH sum for ^{3}He (full circles) and for the neutron (full squares). The HERMES results are plotted on a log scale as open diamonds. Also shown is the result of a calculation using MAID [14].

4. The upgrade to 12 GeV

The research program with the 12 GeV upgrade has two main foci: (1) the experimental confirmation of the origin of quark confinement by QCD flux tubes and (2) the determination of the quark and gluon wave functions. In addition, the upgrade will provide important advances in areas already under study. A detailed overview of the upgrade research program is given in the White Paper [15].

4.1. The accelerator

Each linac tunnel provides sufficient space to install five newly designed cryomodules, each providing 68 MV (compared to the 28 MV from the existing ones). By also replacing up to six of the existing ones the maximum energy gain per pass will be increased from 1.1 to 2.2 GeV, providing a maximum beam energy to Halls A, B and C of 11 GeV. Hall D will be provided with the desired maximum energy of 12 GeV by adding a tenth arc and recirculating the beam through one more linac. A total of 90 μA of CW beam can be provided at the maximum beam energy. An overview of the upgrade of the accelerator is shown in Fig. 5. It is expected that the installation activities will require six months, with an additional six months to fully commission the accelerator in its new configuration.

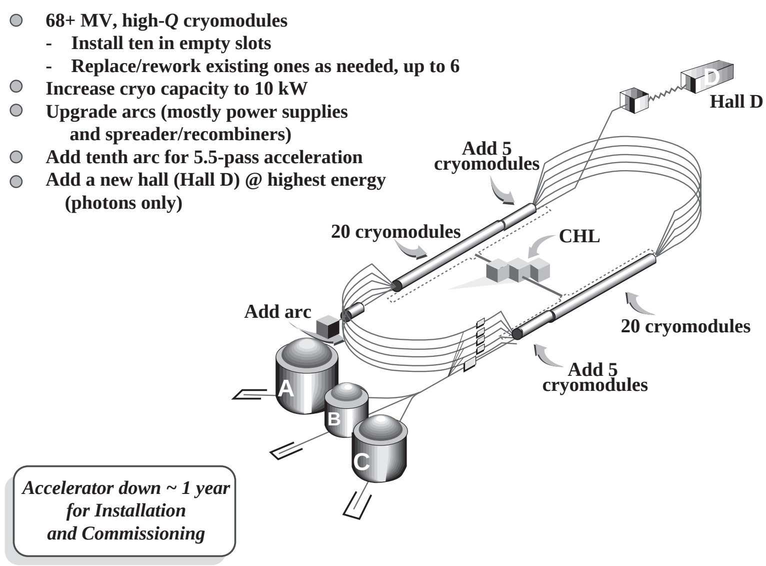

Fig. 5. Overview of the accelerator upgrade to 12 GeV.

4.2. Hall A

With the 12 GeV upgrade a large kinematic domain becomes available for studies of deep inelastic scattering. The combination of high luminosity and high polarization of beam and targets will place Jefferson Lab in a unique position to make significant contributions to the understanding of nucleon and nuclear structure and of the strong interaction in the high-x region.

For example, an accurate measurement of the neutron spin structure functions g_1^n and A_1^n will unambiguously establish the trend of A_1^n when x goes to 1, which will provide a benchmark test of pQCD and constituent quark models. Equivalent measurements for the proton are also intended, as well as measurements of the g_2^n spin structure function and its moments. The latter measurements will provide a clean measure of a higher-twist effect (twist 3), which is related to quark-gluon correlations in the nucleon.

Three instrumentation upgrades in Hall A are proposed to allow an optimal study of the intended experiments: a large-acceptance spectrometer, an electro-magnetic calorimeter and a ^{3}H target. The spectrometer would provide a tool for high-x studies of the properties of nucleons with an 11 GeV beam, where a large acceptance in both solid angle and momentum coupled to a moderate momentum resolution are needed. The availability of a high intensity 11 GeV beam will offer unique possibilities for studying both real and virtual Compton scattering. These experiments require a large, highly segmented, electromagnetic calorimeter.

The proposed MAD (Medium Acceptance Detector) device is a magnetic spectrometer built from two combined-function (quadrupole and dipole) superconducting magnets that can simultaneously produce a 1.5 T dipole field and a 4.5 T/m quadrupole field. The quadrupole components provide the focussing necessary to achieve the desired solid angle while the dipole components provide the dispersion needed for momentum resolution. Optical properties and their impact on the performance have been studied, resulting in a momentum acceptance (resolution) of ±15 (0.2)% and an angular acceptance (resolution) of 30 msr (2 mrad). The maximum central momentum is 6 GeV/c at a total bend angle of 20°. A conceptual design for the MAD support structure has been completed. The device can be withdrawn up the truck ramp to allow operation with the existing HRS pair.

The basic detector package for the MAD spectrometer will cover the full momentum and angular acceptance. The design includes an optional hadron configuration with a flexible particle identification system in the trigger and a very powerful PID in the off-line analysis. The main components of the basic detector package are: high-resolution drift chambers, a hydrogen gas Čerenkov counter, trigger scintillator counters and a lead-glass hadron rejector. The main components of the hadron configuration are: a variable-pressure gas Čerenkov counter, two diffuse-reflective aerogel counters and a Ring Imaging Čerenkov counter.

5. Summary

The results presented provide an essential insight in the transition region between the meson-baryon and the quark-gluon description of hadronic matter, but none shows evidence that the scaling regime of pQCD has been reached at the Q^2-values which can be obtained at the existing JLab facility. The proposed upgrade of the JLab facility to 12 GeV has been described, including the instrumentation under design for Hall A. The research program will be focused on the experimental verification of QCD confinement and a determination of the wave functions of the nucleon constituents.

Acknowledgments

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