Experimental Results in DIS, SIDIS and DES from Jefferson Lab

Sebastian E. Kuhn
Old Dominion University, skuhn@odu.edu

Original Publication Citation

Kuhn, S. E. (2011). Experimental results in DIS, SIDIS and DES from Jefferson Lab. *AIP Conference Proceedings, 1350*(1), 33-38. https://doi.org/10.1063/1.3601370

Experimental Results in DIS, SIDIS and DES from Jefferson Lab

Sebastian E. Kuhn[1]

Old Dominion University, Norfolk, VA 23529, USA

Abstract. Jefferson Lab's electron accelerator in its present incarnation, with a maximum beam energy slightly above 6 GeV, has already enabled a large number of experiments expanding our knowledge of nucleon and nuclear structure (especially in Deep Inelastic Scattering - DIS - at moderately high x, and in the resonance region). Several pioneering experiments have yielded first results on Deeply Virtual Compton Scattering (DVCS) and other Deep Exclusive Processes (DES), and the exploration of the rich landscape of transverse momentum-dependent (TMD) structure functions using Semi-Inclusive electron scattering (SIDIS) has begun. With the upgrade of CEBAF to 12 GeV now underway, a significantly larger kinematic space will become available. The 12 GeV program taking shape will complete a detailed mapping of inclusive, TMD and generalized distribution functions for quarks, antiquarks and gluons in the valence region and beyond.

Keywords: Structure Functions, (Semi-)Inclusive DIS, Deeply Virtual Compton Scattering
PACS: 13.60.Hb

INTRODUCTION

The Continuous Electron Beam Accelerator (CEBAF) at the Thomas Jefferson National Accelerator Facility ("Jefferson Lab") in Newport News, Virginia was originally designed as a "Nuclear Physics" facility with a maximum beam energy of 4 GeV. The incremental increase of the beam energy up to 6 GeV opened up a rich and multi-faceted program of inclusive, semi-inclusive and deep exclusive scattering experiments on (polarized) proton, deuteron, and ^{3}He, as well as nuclear targets, yielding detailed information on the structure of the nucleon and its modification in nuclei. This program will continue with further 6 GeV experiments for the next two years and will then enter a new phase once the energy upgrade to 12 GeV is completed at Jefferson Lab.

CEBAF's very high luminosity polarized and unpolarized targets, highly polarized, intense electron beams and high-resolution spectrometers combine to make it a uniquely powerful tool to study structure functions at high x, where cross sections are small and momentum resolution is important, and at low to moderate Q^2, where one can observe the transition from partonic to hadronic degrees of freedom. The kinematic reach presently stretches from the elastic peak ($W = M_p$) over the nucleon resonance region ($W < 2$ GeV) to the DIS regime (2 GeV $< W <$ 3 GeV), and over nearly 3 orders of magnitude in Q^2, from less than 0.02 GeV^2 to over 6 GeV^2. The upgrade to 12 GeV beam energy more than doubles the reach in Q^2, and extends the x range accessible in DIS from the present $0.1 < x < 0.6$ to $0.06 < x < 0.8$.

[1] Research supported by the US Department of Energy under contract DE-FG02-96ER40960

DIFFRACTION 2010
AIP Conf. Proc. 1350, 33-38 (2011); doi: 10.1063/1.3601370

JEFFERSON LAB FACILITIES

Accelerator. CEBAF is a recirculating linear accelerator with superconducting cavities that can provide continuous electron beams of up to 100 μA simultaneously to up to 3 experimental halls. The injector uses a strained GaAs photocathode that routinely provides polarized electron beams with over 80% polarization. After up to 5 passes around the accelerator, the beam energy in any given hall can range from $\approx$ 400 MeV to presently 6 GeV. The accelerator will be upgraded in the next 3 years to double the beam energy and an additional hall (Hall D) will be added for dedicated tagged photon beam experiments. Construction and detector development for this upgrade has begun.

Hall A. The experimental equipment in Hall A [1] consists of two symmetric high-resolution spectrometers, a larger acceptance detector ("BigBite") and various targets and ancillary equipment. The spectrometers have a momentum resolution of 2×10^{-4} and enable running with very high luminosity, in excess of 10^{38} cm^{-2}s^{-1}. In addition to high-power cryogenic and solid targets spanning nuclei up to lead, experiments can also use the highest-luminosity and highest polarization gaseous polarized ^{3}He target in the world to study the structure both of the neutron and the ^{3}He nucleus. Plans for the upgrade include a large acceptance "Super-BigBite" spectrometer and other dedicated detectors.

Hall B. Jefferson Lab's Hall B houses the CEBAF Large Acceptance Spectrometer (CLAS) [2], which is based on a toroidal magnetic field (produced by 6 superconducting coils) surrounding the beam. CLAS can detect several particles emitted in a reaction simultaneously, over a scattering angle range of $6^\circ < \theta < 140^\circ$ and nearly 2π in azimuth. While the luminosity is limited to a few times 10^{34} cm^{-2}s^{-1}, inclusive, semi-inclusive and exclusive data can be collected over a large kinematic range simultaneously, and CLAS is especially well matched to cryogenic polarized targets (NH_3 and ND_3) with their own luminosity limitations. During the upgrade, CLAS will be replaced by a new version ("CLAS12") consisting of a forward toroid (to detect scattered electrons and fast hadrons) and a central solenoid tracker to detect the recoiling target or its fragments. CLAS12 will run with up to 10 times higher luminosity.

Hall C. Experiments in Hall C can use two standard spectrometers (High Momentum - HMS - and Short Orbit - SOS) as well as dedicated, specialized equipment. A recent addition has been the BETA detector that consist of a large acceptance calorimeter and matched Cherenkov counter. The achievable luminosities are similar to Hall A. Cryogenic and solid targets have been used to measure inclusive structure functions on nucleons and nuclei. In addition, polarized NH_3 and ND_3 targets are also available. For the 12 GeV future, a new detector (Super-HMS) will be built to measure structure functions and form factors at the highest possible momentum transfers.

In the following, I will outline the Physics topics that can be studied at Jefferson Lab and describe a few sample experiments and results from the already completed program. Further information can be found at the posted version of my talk [3] and at the Jefferson Lab website [4].

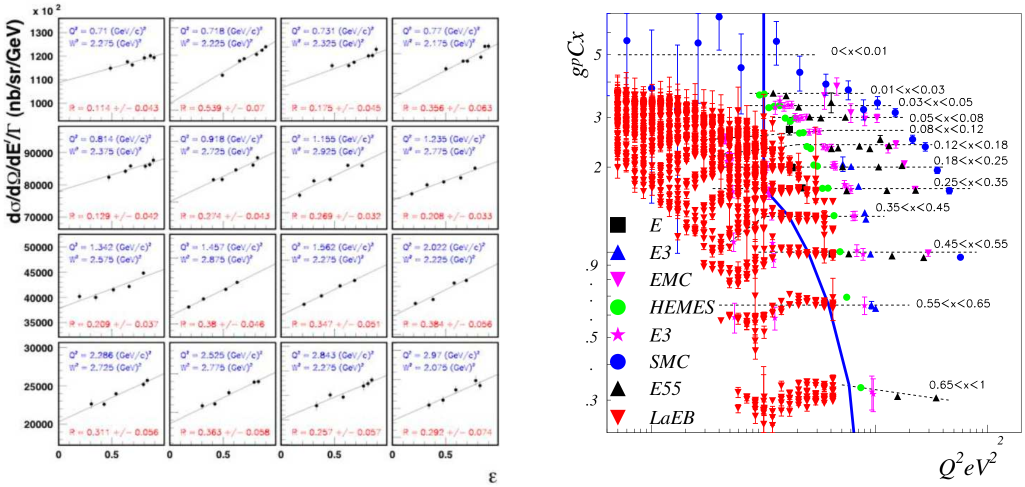

FIGURE 1. Sample results for structure functions measured at Jefferson Lab. Left: Rosenbluth separation of the structure functions F_L and F_1 of the proton in the resonance region, measured in Hall C. Right: The range in Q^2 and x covered by measurements of g_1^p with CLAS in Hall B.

PHYSICS TOPICS

Inclusive DIS

Unpolarized structure functions have been measured world wide over a huge range in Q^2 and x, and parton distribution functions (PDFs) for all quark flavors and gluons have been extracted. There still remain large uncertainties at very large x, where valence quarks dominate and predictions from pQCD and from quark models differ significantly. The structure function F_L is less well known than F_2, as are the polarized structure functions (g_1 and g_2), where the leverarm in Q^2 from existing measurements is much more modest and the precision at large x is even lower. To determine moments of these structure functions and to extract higher twist contributions in the framework of the Operator Product Expansion (OPE) one needs precise measurements at high x and down to rather low Q^2. These measurements can help us understand the phenomenon of quark-hadron duality in DIS and the transition from sum rules (like the Gerasimov-Drell-Hearn sum rule [5]) involving low-energy properties of the nucleon with pQCD sum rules like the Bjorken sum rule [6]. Jefferson Lab is uniquely positioned to make significant contributions in all of these areas, both due to the very high statistical and systematic precision of its data and due to its kinematics which emphasize large x and low to moderate Q^2.

Figure 1 shows two examples of the very comprehensive data sets already collected for the structure functions F_1, F_L and g_1 for the proton, covering nearly all of the accessible kinematics. Similar data sets exist for the deuteron and, in the case of g_1, for ^{3}He (Hall A), which can be considered an "effective neutron target". Data have also been collected on g_2 for all three targets in Halls A and C, and further experiments are planned for Hall A. The data set for g_1^p and (to a lesser extent) g_1^d has been further

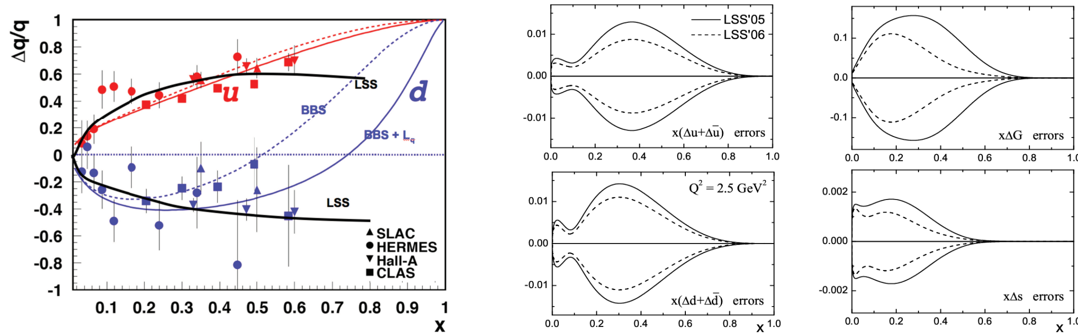

FIGURE 2. Left: Quark polarizations $\Delta u/u$ (upper half) and $\Delta d/d$ (lower half) extracted from inclusive measurements of A_1 (Halls A and B, and from SLAC) and semi-inclusive measurements of flavor-tagged structure functions (HERMES). The curves are explained in the text. Right: Uncertainty on polarized parton distributions before (solid line) and after (dashed line) including the results from Jefferson Lab (and COMPASS) in a DGLAP analysis.

increased significantly (with much better statistics) by experiments in Hall B and Hall C which are still under analysis.

The data on F_2 and F_L have been used for detailed investigations of quark-hadron duality (which seems to hold for both of these structure functions) and to evaluate Nachtmann moments and higher twist matrix elements. The data on g_1 have been used to study the asymptotic behavior of the up and down quark polarizations as $x \to 1$, see Fig. 2. While the kinematic reach is still limited (to $x \leq 0.6$), there is a clear discrepancy with pQCD expectations (dashed curves labeled "BSS" [7]), especially for the d-quark polarization, which remains negative out to the highest measured x, in agreement with PDF fits (e.g., by Leader, Stamenov and Siderov [8] - the curves labeled "LSS"). On the other hand, a pQCD curve that includes the possible effects of quark orbital angular momentum ("BSS + L_q" [9], solid curves) is in better agreement with the data and can be tested conclusively with the 12 GeV beam of the upgraded Jefferson Lab. In addition, the polarized data have also been used in various NLO fits of polarized PDFs, leading to a significant decrease in their uncertainties because of the very precise "anchoring" at low Q^2 of the DGLAP evolution. As an example, the decrease in the errors on several PDFs due to the inclusion of Jefferson Lab (and COMPASS) data by LSS [8] is also shown in Fig. 2. Again, a significant further reduction of these uncertainties is expected with the advent of 12 GeV data. Finally, a novel approach to measuring neutron structure functions out to large x without the large nuclear uncertainties usually associated with the use of deuterons as "effective neutron targets" has been pioneered with CLAS. A compact cylindrical time projection chamber with radial readout (RTPC) was developed and integrated with a very thin deuterium target into CLAS to fully reconstruct the tracks of slow ($p \leq 100$ MeV/c), backward moving protons released as "spectators" in coincidence with the electron scattered by the neutron. This "tagging" method allowed us not only to minimize the contribution from the high momentum tail of the deuteron wave function (where binding effects might be significant) but also to fully reconstruct the kinematics and thereby avoid the usual Fermi-smearing of bound structure functions. The final results from this "BoNuS" experiment will be published shortly.

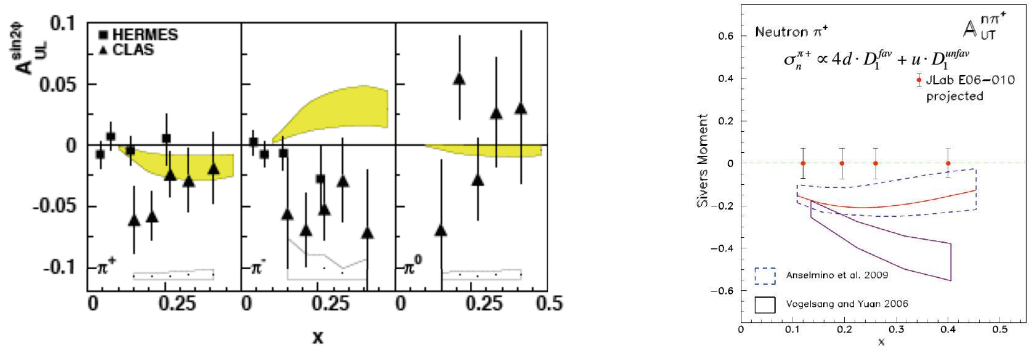

FIGURE 3. Left: $\sin(2\phi)$ moments of single (longitudinal) target spin asymmetries for all three charge states of the pion, vs. x, from Hall B. Right: Expected precision for data on the Sivers moment of transverse single spin asymmetries measured on ^{3}He in Hall A, together with predictions.

Semi-inclusive DIS

By detecting (at least) one leading hadron (with relatively high $z = E_h/\nu$), one can gain further information about the struck quark in DIS, in particular its flavor. Recently, interest in SIDIS has seen a huge surge because of the connection to novel (unintegrated) structure functions, which can reveal the full three-dimensional structure of the nucleon, including transverse parton momenta and their correlation with nucleon and parton spin (TMDs). SIDIS is also one of only two processes that can directly access the third fundamental structure function of the nucleon, h_1 (transversity). Because of the required binning of SIDIS data in the additional variables describing the outgoing hadron (z, p_T and ϕ), large acceptance and large luminosities are of great importance, giving Jefferson Lab again an important role to play.

Data have already been taken on unpolarized SIDIS in Halls B and C, for several leading hadrons ($\pi^\pm, K^\pm$). These data show that factorization works reasonably well even at Jefferson Lab with 6 GeV and give a first glimpse at transverse momentum dependent PDFs. Hall B has published first results for longitudinally polarized p and d targets (double and single spin asymmetries), and in Hall A, an experiment to measure both Collins and Sivers moments of single spin asymmetries with a transverse ^{3}He target has been completed and is nearing publication (see Fig. 3). The Hall B data, which shed light on the transverse momentum distribution of quarks with opposite helicity and give a glimpse of the Collins effect (in conjunction with the so-called "worm gear PDF", see Fig. 3 left) have meanwhile be augmented by an order of magnitude higher statistics (under analysis). The SIDIS program for 12 GeV aims at a comprehensive map of all TMDs in the accessible x range and will involve all three Halls.

Hard Exclusive Processes

A three-dimensional picture of the nucleon somewhat complementary to that accessed by SIDIS comes from the detailed study of Generalized Parton Distributions (GPDs) which depend simultaneously on the (Fourier transform of the) transverse position and on the longitudinal momentum fraction x of quarks and gluons. They encompass, as their limiting cases, both DIS structure functions and elastic form factors. Experimentally, information on GPDs can be gathered from Hard Exclusive Processes, where a virtual photon with (relatively) large Q^2 is absorbed by a nucleon which stays intact and emits a hadron or photon carrying most of the virtual photon momentum in the final state. In particular the case of real photon emission (Deeply Virtual Compton Scattering - DVCS) has a rather clean connection to the underlying GPDs and, again, has received much experimental and theoretical attention recently. Jefferson Lab is well situated to contribute significant data, in particular on quark GPDs at moderate to high x. High precision and high luminosity are again of great advantage.

After some initial results from analyzing CLAS data collected for other purposes (enabled by its large acceptance and open trigger), a dedicated program of measuring DVCS is ongoing in Halls A and B. CLAS measurements on the beam spin asymmetry (BSA) for H$(e,e'\gamma p)$ have been carried out over a fairly wide range of x (0.13 – 0.46), Q^2 (1.2 – 3.7 GeV^2) and t. These data are beginning to constrain parametrizations of GPDs. A new, dedicated experiment presently under analysis complements this information with data on *target* single spin asymmetries, which are sensitive to different combinations of GPDs. In Hall A, a very precise measurement of both BSA and absolute cross sections for DVCS on both the proton and (using a deuterium target) the neutron has yielded new constraints on the total angular momentum carried by valence quarks (via the Ji Sum Rule [10]) and supported the onset of factorization even at 6 GeV kinematics. This experiment is presently followed up by a more extensive and precise measurement of absolute cross sections, again on both proton and neutron. Measurements of cross section and all possible combinations of target and beam asymmetries, over a wide kinematic range, are one of the central goals of the 12 GeV program at Jefferson Lab. The upgraded CLAS12 spectrometer was optimized to cover the kinematics of both the photon and the recoil nucleon in DVCS nearly hermetically (via a small-angle calorimeter and a dedicated central tracker). Complementary experiments have also been proposed for Hall A, using both existing as well as potential new detectors.

In summary, the 12 GeV era will complete the emerging three-dimensional picture of the nucleon in the range of $0.06 \leq x \leq 0.8$, where valence quark configurations dominate its structure. The existing 6 GeV experiments have already yielded important information and have laid the groundwork for a successful program at 12 GeV.

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