Measurement of The Deep-inelastic Spin-dependent Structure Functions of The Proton and Neutron at HERA

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In this letter we propose to measure the deep-inelastic spin-dependent structure functions $g_1^p(x)$ and $g_1^n(x)$ for the proton and neutron using internal polarized targets and the longitudinally polarized 30 GeV electron beam in the HERA electron storage ring. The measurement of the deep-inelastic spin-structure of both isospin states of the nucleon at the same kinematics and using the same apparatus is interesting for the following reasons:

a) It allows the Bjorken sum rule to be experimentally checked.

b) It uniquely constrains the spin distribution of the $u$ and $d$ quarks as a function of $x$ in any model of the nucleon.

c) It allows the total fraction of the spin of the nucleon carried by the quarks to be deduced. This quantity is of astrophysical significance since the magnitude of the interaction of any photino component of dark matter in the universe depends on it.

Recently measurements have been presented of the asymmetries in polarized muon-polarized proton deep inelastic scattering.\(^1\) The spin-dependent structure function $g_1^p(x)$ was deduced from these measurements. The data indicate that the Ellis-Jaffe sum rule\(^2\) for the proton is violated. Assuming the Bjorken sum rule\(^3\) is valid, the data imply that the neutron must have a much larger contribution to it than hitherto assumed\(^4\), with the asymmetry for the neutron being largely negative over at least part of the $x$ range. No data on the neutron exist. Also the new data can be interpreted to indicate that the fraction of the proton spin carried by the quarks is small\(^1\).
In deep inelastic scattering the measured asymmetry

\[ A = \frac{d\sigma^\uparrow \downarrow - d\sigma^\downarrow \uparrow}{d\sigma^\uparrow \downarrow + d\sigma^\downarrow \uparrow} \]

is related to the virtual photon asymmetries \( A_1 \) and \( A_2 \) by

\[ A = D(A_1 + \eta A_2) \]

where \( D \) and \( \eta \) are kinematic depolarization factors. Here

\[ A_1 = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} \]

where \( \sigma_{\frac{1}{2}} (\sigma_{\frac{3}{2}}) \) is the cross section when the virtual photon-target system is in the state \( J_z = \frac{1}{2} (\frac{3}{2} \frac{1}{2}) \). The asymmetry \( A_2 \) is due to transverse-longitudinal interference and should be small. It is expected to be sensitive to the transverse spin components of the nucleon in the infinite momentum frame. No experimental information on \( A_2 \) exists for either isospin state of the nucleon. Since \( \eta \) is also small \( A_1 \approx A/D \). In the scaling limit, the structure function \( g_1(x) \) is related to \( A_1(x) \) by

\[ g_1^{p(n)}(x) = \frac{A_1^{p(n)}(x)F_2^{p(n)}(x)}{2x [1 + R(x)]} \]

where \( R(x) = \sigma_L/\sigma_T \), and \( F_2^{p(n)}(x) \) are the unpolarized structure functions.

Sum rules govern the behavior of \( g_1(x) \). The Bjorken sum rule, derived from light-cone algebra, relates the integral of \( g_1(x) \) to the axial vector and vector coupling constants, \( g_A \) and \( g_V \), measured in nucleon \( \beta \) decay. After correction for QCD radiative effects, this is given by

\[ \int_0^1 \left[ g_1^p(x) - g_1^n(x) \right] dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \cdot \left( 1 - \frac{\alpha_s(Q^2)}{\pi} \right) \]

where the superscripts \( p(n) \) refer to the proton (neutron) and \( \alpha_s(Q^2) \) is the running coupling constant of QCD. This is a deeply fundamental sum rule and its violation would be unexplainable in the quark parton model of the nucleon. A sum rule of such importance needs to be checked and to do this, measurements of both \( g_1^p(x) \) and \( g_1^n(x) \) are necessary.
Assuming SU(3) symmetry and that the strange sea quarks are unpolarized, Ellis and Jaffe derived separate sum rules for the neutron and proton. These are

\[ \int_0^1 g_1^{(n)}(x)dx = \frac{1}{12} \frac{g_A}{g_V} \left[ -1 + \frac{5}{3} F - D \right] \]
\[ = 0.189 \quad \text{(proton)} \]
\[ = -0.002 \quad \text{(neutron)} \]

where \( F \) and \( D \) are the form factors measured in baryon decay. The EMC measurement\(^1\) gives

\[ \int_0^1 g_1^{p}(x)dx = 0.113 \pm 0.012 \pm 0.025 \]

indicating that this sum rule is violated. This probably means that the assumptions made in deriving the sum rule are wrong, and Jaffe has conjectured that the violation may be associated with the non-conservation of the U(1) axial current in QCD\(^6\). However, it could also be a consequence of the violation of the Bjorken sum rule. Clearly measurement of \( g_1^{n}(x) \) would provide the crucial information necessary to answer this question.

It is possible to search for heavy cold dark matter particles such as the photino (\( \tilde{\gamma} \)) via elastic scattering in conventional matter. The matrix element \( A(\tilde{\gamma}N \rightarrow \tilde{\gamma}N) \) for \( \tilde{\gamma} \)-nucleon scattering is proportional to the integral of \( g_1(x) \) i.e.

\[ A(\tilde{\gamma}N \rightarrow \tilde{\gamma}N) \propto \int_0^1 g_1(x)dx. \]

The recent EMC data reduce the value of \( \sigma(\tilde{\gamma}p \rightarrow \tilde{\gamma}p) \) by about a factor of three, compared to the previous canonical estimate. This has direct implications for the photino trapping rate in the sun, as well as estimates of the elastic scattering rate. In the shell model, estimates of rates on materials dominated by proton matrix elements are reduced, while those dominated by neutron matrix elements are enhanced\(^5\).

In principle, the combination of \( g_1^{p}(x) \) and \( g_1^{n}(x) \) together contain all the information necessary to determine the spin structure of the quarks inside the nucleon. However, present quark models of the nucleon are not based on rigorous QCD calculations (although in the future they may be). Thus, measurement of the spin-dependent structure functions of the proton and neutron serves as a very tight constraint on existing models of the nucleon.
and also as an aid to developing improved models. As an example of the ability of the data to set constraints on models, consider the new EMC measurements. If this data is analyzed in the simplest quark parton picture the fraction of the total spin of the nucleon carried by the quarks is very small. It is also worth remarking that the effect of gluons on the spin-dependent structure functions is a largely unexplored matter. Finally, the entire field of high energy interactions of polarized hadrons depends on an understanding of the spin-structure of the nucleon.

To measure the asymmetries in deep inelastic scattering of polarized electrons from polarized protons and neutrons we propose a new technique. This is to use internal polarized atomic gas targets of density $10^{14}$ to $10^{15}$ cm$^{-2}$ and polarization 50% placed in the 60 mA circulating polarized electron beam of the HERA storage ring. To study the proton a polarized atomic hydrogen target will be used. For the neutron, polarized $^3$He will be used, since to a good approximation the two protons in this nucleus have opposite spins, and so the asymmetry is due to the neutron. In addition, we would measure the asymmetry from a polarized deuteron target. This would be an independent method of determining the neutron spin-dependent structure functions. These measurements become possible because of both the development of a new generation of polarized hydrogen, deuteron, and $^3$He targets based on the method of optical pumping and the availability of longitudinally polarized electrons in the HERA electron storage ring. These targets provide a luminosity of about $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and have the advantage of requiring only a weak holding magnetic field.

The proposed technique does not suffer the disadvantages of conventional polarized target technology. (In the conventional approach, polarized deuterons in the form of deuterated ammonia would be used, necessitating the subtraction of the large proton asymmetry to determine the small neutron asymmetry. In addition, the asymmetry is diluted by scattering from large amounts of unpolarized material in the ammonia target. In our method, the polarized atoms are pure atomic species.) Because our proposed target thickness is of order 10$^{-10}$ radiation lengths, the contribution from external radiative corrections in the target is negligible. Also, the small holding field of the optically pumped targets permits the trivial rotation of the spins through 90° to measure the transverse-longitudinal interference asymmetry $A_2$. 
A schematic diagram of a possible configuration of the polarized \(^3\)He internal target is shown in Fig. 1. An infrared laser optically pumps a sample of \(^3\)He at a density of \(10^{16}\) atoms \(\text{cm}^{-3}\) contained in a pyrex cell. This cell is connected through a narrow tube to a 10 cm long “bottle”. This “bottle” has long tubes of length 1 m and i.d. 12.5 mm at each end to act as an impedance for the gas flow. The narrow tubes are each made in two pieces so that they can be opened up during injection of the stored electron beam. The tubes will also need cooling because of the 500 W of power deposited through rf heating by the beam in the central target region. A weak holding magnetic field is required for the optical pumping process. The presence of a \(10^{15}\) cm\(^{-2}\) target in an electron ring will give rise to multiple scattering and Bremsstrahlung losses. We estimate the beam lifetime due to these effects to be of order 100 hours.

Fig. 2 shows a possible detector configuration for this experiment. Clearly we require that the proton beam does not pass through the target. This implies that either the experiment runs in parasitic mode with the proton beam displaced from the electron beam or that the experiment is run in dedicated mode with the proton beam turned off. The detector consists of a 1 Tm \(\times\) 1 m gap dipole magnet through which both the scattered particles and the stored electron beam pass. A superconducting tube shields the electron beam from the dipole field. Planes of MWPCs allow the tracking of charged particles and a wall of lead-glass serves as a calorimeter to measure the energy. The detector should have large acceptance for electrons with scattering angles between 5° and 25°.

Fig. 3 shows the precision as a function of \(x\) and \(Q^2\) attainable in a 240 hour run at HERA in a measurement of \(A_1^p(x)\) on the polarized \(^3\)He target. It is assumed that the 30 GeV electron beam and target polarizations are each 0.5; the electron beam current is 60 mA; the incident electron energy is taken to be 30 GeV; a dilution factor of 0.33 is used because the electron can also scatter from the two protons in the \(^3\)He nucleus. The region in \(x\) extends from 0.02 to 0.8 and in \(Q^2\) from 1 to 20 (GeV/c\(^2\)). The low \(x\) limit is determined by elastic radiative tails and backgrounds at high \(y = \frac{Q^2}{E}\). Systematic errors of \(\pm 5\%\) for the target polarization and \(\pm 10\%\) for the electron polarization have been included. The solid line in this figure is the prediction of a modified Carlitz-Kaur model which is in good agreement with the new EMC data and is constrained to obey the Bjorken sum
rule\textsuperscript{8}. To check out the apparatus and to make a complete set of measurements on the proton and neutron, ($A_1^p(x)$, $A_2^p(x)$, $A_3^p(x)$, and $A_2^n(x)$) we estimate that we would need on the order of one year of beam time.

In summary, we would propose a set of precise and fundamental measurements on the spin structure of the nucleon at HERA. These are made possible by recent advances in both polarized target and polarized electron beam technology. It is important that these measurements be carried out, especially in the light of recent data, which indicate that our understanding of the spin-structure of the nucleon is very incomplete.

References

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PRELIMINARY DESIGN OF POLARIZED $^3$He INTERNAL TARGET

Figure 1.
30 GeV $e^-$ beam → polarized internal target → dipole magnet for momentum analysis → wire chambers → Pb-glass energy calorimeter → $e^-$ beam