New proton polarized structure functions
in charged current processes at HERA

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Abstract:
Estimates for longitudinal spin asymmetries which single out new polarized nucleon
structure functions in deeply inelastic charged current interactions at HERA energies
are given, exploiting their interpretation in terms of polarized quark distributions.
These asymmetries turn out to be large and allow a measurement of the new polar-
ized structure functions $g_1^W$ and $g_5^W$, which would add valuable tests and information
on the spin content of quarks inside a polarized proton. We also show that single
spin asymmetries in neutral current interactions are very small.

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The possible availability of a polarized proton beam at HERA, with polarized lepton-proton scattering at $Q^2$ values up to a few thousands of GeV$^2$, allows a new investigation of proton spin effects in charged current (cc) interactions \[1\]. This gives access to new polarized proton structure functions which would offer novel information on polarized quark distributions, because charged current events probe combinations of spin-dependent quark distributions different from those probed in electromagnetic processes \[2\]-\[6\]. It is then clear the importance of such future HERA spin program.

We give here simple estimates of double longitudinal spin asymmetries in $\ell^+ p \to \nu(\bar{\nu})X$ processes which, if measured, would yield direct information on new structure functions, including polarized parity violating ones. It turns out that such asymmetries are large, much larger than the expected statistical errors, and can be safely measured, provided charged current events may be detected, which is expected. More spin asymmetries and their content in terms of structure functions and quark distributions are discussed in Ref. \[3\].

According to the conventions and notations of Ref. \[3\], the cross-section for the weak interaction of a longitudinally polarized lepton (with helicity $\lambda/2$) with a longitudinally polarized nucleon (with spin four-vector $S = S_L$) in the charged current process $\ell^\mp p \to \nu(\bar{\nu})X$ is given by (neglecting terms of order $m_N/E_N$):

$$\frac{d^2\sigma_{cc}^{\ell^\mp p}(\lambda, S_L)}{dx\,dQ^2} = \frac{G^2M_W^4}{4\pi} \frac{(1 \mp \lambda)}{(Q^2 + M_W^2)^2} \left\{ (y^2 - 2y + 2)F_{1W}^\ell \mp \frac{\lambda y(2-y)}{2}F_{3W}^\ell \right\}.$$  

(1)

Notice that this implies $\lambda = -1$ for negatively charged leptons, $\ell^-$, and $\lambda = +1$ for positively charged ones, $\ell^+$. When reversing the nucleon spin ($S_L \to -S_L$) the terms in $g_1^W$ and $g_5^W$ change sign.

By setting

$$a \equiv 2(y^2 - 2y + 2), \quad b \equiv y(2-y),$$  

(2)

Eq. (1) can be written in a simple form as

$$\frac{d^2\sigma_{cc}^{\ell^\mp p}(\lambda = \mp 1, S_L)}{dx\,dQ^2} = \frac{1}{4\pi} \frac{G^2M_W^4}{(Q^2 + M_W^2)^2} \left\{ a\left[F_{1W}^\ell \mp g_5^W\right] \pm b\left[F_{3W}^\ell + 2g_1^W\right]\right\},$$  

(3)

where the $\mp$ refer respectively to $\ell^-$ and $\ell^+$. In case the leptons were not 100% polarized (that is $\langle \lambda \rangle \neq \mp 1$) the r.h.s. of the above equation should be multiplied by an overall factor $(1 \mp \langle \lambda \rangle)/2$; for unpolarized leptons ($\langle \lambda \rangle = 0$) this amounts to a factor $1/2$.

It is now immediate to compute the double spin asymmetry

$$A_{cc}^{\ell^\mp p}(\mp, S_L) = \frac{d^2\sigma_{cc}^{\ell^\mp p}(\mp, S_L) - d^2\sigma_{cc}^{\ell^\mp p}(\mp, -S_L)}{d^2\sigma_{cc}^{\ell^\mp p}(\mp, S_L) + d^2\sigma_{cc}^{\ell^\mp p}(\mp, -S_L)} = \frac{\pm 2b g_1^W + a g_5^W}{a F_{1W}^\ell \pm b F_{3W}^\ell}.$$  

(4)
Notice that the same result holds with unpolarized leptons, as the $cc$ interactions single out definite lepton helicities.

Recalling the quark parton model expression of the structure functions $[3]$, 

\[ g_{W^-}^1 = \Delta u + \Delta c + \Delta \bar{d} + \Delta \bar{s} \] 
\[ g_{W^-}^5 = \Delta u + \Delta c - \Delta \bar{d} - \Delta \bar{s} \] 
\[ g_{W^+}^1 = \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{c} \] 
\[ g_{W^+}^5 = \Delta d + \Delta s - \Delta \bar{u} - \Delta \bar{c} \] 

one has, respectively for charged current processes initiated by negatively or positively charged leptons:

\[ A_{W^-} = \frac{(\Delta u + \Delta c) - (1 - y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u + c) + (1 - y)^2(d + \bar{s})} \] 
\[ A_{W^+} = \frac{(1 - y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1 - y)^2(d + s) + (\bar{u} + \bar{c})} \] 

Other interesting combinations of polarized quark distribution functions may be obtained if one could combine data taken with $\ell^-\bar{\ell}$ and $\ell^+\bar{\ell}$ beams. This is discussed in detail in Ref. $[3]$. Notice that, in principle, one might easily extract information on parity violating polarized structure functions also by considering a single spin asymmetry in neutral current ($nc$) processes with longitudinally polarized protons and unpolarized leptons $[3, 4]$. The spin asymmetry for unpolarized electrons reads $[3]$

\[ A_{n_{\ell}^p}^{\gamma\ell^-} = \eta^{\gamma Z} \frac{a}{2} \left[ (2s_w^2 - \frac{1}{2})g_{5Z}^1 + \eta^{\gamma Z}(4s_w^4 - 2s_w^2 + \frac{1}{2})g_{5Z}^5 \right] - b \left[ g_{1Z}^1 + \eta^{\gamma Z}(4s_w^2 - 1)g_{1Z}^1 \right] \]
\[ a \left[ F_{1Z}^1 + \eta^{\gamma Z}(2s_w^2 - \frac{1}{2})F_{1Z}^1 \right] - \frac{1}{2}b \eta^{\gamma Z} F_{3Z}^1 + O[(\eta^{\gamma Z})^2] \]

where

\[ \eta^{\gamma Z} = \frac{GM_Z^2}{2\sqrt{2}\pi\alpha Q^2 + M_Z^2} \]

$s_w$ is the sine of the Weinberg angle, and we have neglected in the denominator the purely weak contributions, of $O[(\eta^{\gamma Z})^2]$ and negligible in most of HERA $Q^2$ range where $\eta^{\gamma Z}$ is still rather small. The expression of the structure functions $g_{1Z}^1$ and $g_{3Z}^1$ in terms of quark distributions can be found in Ref. $[3]$. In the numerical analysis we use a lepton energy $E_\ell = 27.6$ GeV and a proton beam energy of 820 GeV and impose the following kinematical cuts: $0.01 < y < 0.9$, $x < 0.7$. In addition, in the $cc$ case we apply a cut on the missing transverse momentum, $P_T > 15$ GeV, and in the $nc$ case we demand $Q^2 > 500$ GeV$^2$. The leading order polarized parton distributions are taken from Ref. $[7]$ (here we use the set “standard scenario”, eventually extrapolated to $Q^2$ values greater than $10^4$ GeV$^2$; the “valence” set yields very similar results); the unpolarized ones are taken

3
We have assumed fully polarized beams, but we emphasize that $A^{W\pm}$ are independent of the degree of polarization of the lepton beam, and proportional to the polarization of the proton: $|\langle \lambda_\ell \rangle| < 1$ would only marginally decrease the available statistical precision, while $|\langle \lambda_p \rangle| < 1$ would simply reduce the asymmetries by the corresponding factor. A high degree of polarization of the proton beam, more than that of the leptons, would be a most welcome feature.

In Figs. 1 – 6 we show the expected asymmetries as functions of $x$ both at fixed $Q^2 = 1000$ GeV$^2$ and averaging over all the kinematically allowed $Q^2$ region, that is summing all detectable events in a given $x$-bin. The statistical errors shown in the figures have been calculated from

$$\delta A = \frac{\sqrt{1 - A^2}}{\sqrt{2L(d^2\sigma/dxdQ^2)\Delta x\Delta Q^2}}$$

assuming that for each longitudinal proton polarization an integrated luminosity $L = 500$ pb$^{-1}$ can be collected. [To calculate the errors at fixed $Q^2$ we take $\Delta Q^2 = Q^2/2$.] It is interesting to note that for relatively low $Q^2 (\approx 10^3$ GeV$^2$) and in the kinematically allowed region, $a \gg b$, so that the asymmetries are dominated by the parity violating form factor $g_5$. This hints to the possibility of a direct extraction of this interesting quantity from the asymmetry.

We find that in the $cc$ case the spin asymmetries, both in $e^-p$ and $e^+p$ processes, are large (up to 60%) and measurable in an upgraded HERA experiment. As the statistical errors scale like $1/\sqrt{L}$, a reasonable precision can be achieved even with an integrated luminosity of only $L = 50$ pb$^{-1}$ per polarization. On the other hand, in the $nc$ case the spin asymmetry is much too small to be meaningfully measured at HERA, as an effect of the dominant parity conserving electromagnetic contribution.

In summary, we have clearly shown that measurements of charged current processes in deep inelastic scattering of longitudinally polarized or unpolarized leptons off longitudinally polarized protons at HERA energies offer a unique and viable way of reaching more information on the quark spin content of protons; predictions based on the actual knowledge of the polarized quark distributions are given.

Upon completion of this analysis we learned that similar conclusions for the spin asymmetries have been obtained in Ref. [9].
References

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Figure 1: Charged current $e^-p$ spin asymmetry, Eq. (9) of text, for $Q^2 = 1000$ GeV$^2$, at HERA energies with fully polarized beams. Statistical errors calculated for $\mathcal{L} = 500\,pb^{-1}$ and $\Delta Q^2 = 500$ GeV$^2$ for each polarization are shown.

Figure 2: Charged current $e^-p$ spin asymmetry, Eq. (9) of text, averaged over the allowed $Q^2$ region, at HERA energies with fully polarized beams. Statistical errors calculated for $\mathcal{L} = 500\,pb^{-1}$ for each polarization are shown.
Figure 3: Charged current $e^+p$ spin asymmetry, Eq. (10) of text, for $Q^2 = 1000$ GeV$^2$, at HERA energies with fully polarized beams. Statistical errors calculated for $\mathcal{L} = 500\, pb^{-1}$ for each polarization and $\Delta Q^2 = 500$ GeV$^2$ are shown.

Figure 4: Charged current $e^+p$ spin asymmetry, Eq. (10) of text, averaged over the allowed $Q^2$ region, at HERA energies with fully polarized beams. Statistical errors calculated for $\mathcal{L} = 500\, pb^{-1}$ for each polarization are shown.
Figure 5: Neutral current $e^{-}p$ single spin asymmetry, Eq.(11) of text, for $Q^2 = 1000 \text{ GeV}^2$ at HERA energies with fully polarized proton beams. The statistical errors calculated for $\mathcal{L} = 500 \text{ pb}^{-1}$ for each polarization and $\Delta Q^2 = 500 \text{ GeV}^2$ are shown.

Figure 6: Neutral current $e^{-}p$ single spin asymmetry, Eq.(11) of text, averaged over the allowed $Q^2$ region at HERA energies with fully polarized proton beams. The statistical errors calculated for $\mathcal{L} = 500 \text{ pb}^{-1}$ for each polarization are shown.