Experiment E04-113 at Jefferson Lab Hall C plans to measure the beam-target double-spin asymmetries in semi-inclusive deep-inelastic $\vec{p}(e,e'p)X$ and $\vec{d}(e,e'h)X$ reactions ($h = \pi^+, \pi^-, K^+, \text{or } K^-$) with a 6 GeV polarized electron beam and longitudinally polarized NH$_3$ and LiD targets. The high statistic data will allow a spin-flavor decomposition in the region of $x = 0.12 \sim 0.41$ at $Q^2 = 1.21 \sim 3.14$ GeV$^2$. Especially, leading order and next-to-leading order spin-flavor decomposition of $\Delta u$, $\Delta d$, and $\Delta \bar{u} = \Delta \bar{d}$ will be extracted based on the measurement of the combined asymmetries $A_{1N}^{s,s}$. The possible flavor asymmetry of the polarized sea will be addressed in this experiment.

1. Introduction

Remarkable progress in the knowledge of the polarized quark distributions $\Delta q_f(x)$ has been made in the last decade through inclusive deep-inelastic lepton scattering (DIS). However, the information available from inclusive DIS process has inherent limitations. As the cross sections are only sensitive to $e^2 q^4$, an inclusive DIS experiment probes quarks and anti-quarks on an equal footing, therefore is not sensitive to the symmetry breaking in the sea sector. The sensitivity to each individual quark flavor can be realized in semi-inclusive deep inelastic scattering (SIDIS) in which one of the leading hadrons is also detected. Recently, the HERMES collaboration published the results of a leading order spin-flavor decomposition from polarized proton and deuteron data, and for the first time extracted the $\bar{u}, \bar{d}$ and $s = \bar{s}$
The validity of the HERMES method of spin-flavor decomposition relies explicitly on several non-trivial assumptions. First, the leading-order “naive $x$–$z$ factorization” was assumed and the next-to-leading order terms were neglected. This implies that the cross sections factorize into the $x$-dependent quark distributions and the $z$-dependent fragmentation functions:

$$\sigma^h(x, z) = \sum_i e_f^2 q_i(x) \cdot D^h_{q_i}(z),$$
$$\Delta \sigma^h(x, z) = \sum_i e_f^2 \Delta q_i(x) \cdot D^h_{q_i}(z).$$

(1)

Furthermore, it was assumed that the quark fragmentation process and the experimental phase spaces were well-understood such that a LUND model based Monte Carlo simulation program can reliably reproduce the “purity matrices” which account for the probability correlations between the detected hadrons and the struck quarks.

It was pointed out by Christova and Leader that if the combined asymmetries $A_{1N}^{\pi^+ - \pi^-}$ are measured, quark polarization $\Delta u_v$, $\Delta d_v$ and $\Delta \bar{u} - \Delta \bar{d}$ can be extracted at leading order without the complication of fragmentation functions. Even at next-to-leading order, information on the valence quark polarizations is well preserved in the combined asymmetries $A_{1N}^{\pi^+ - \pi^-}$.

2. The Christova-Leader method at LO and NLO

At the leading order, under isospin symmetry and charge conjugation, the fragmentation functions cancel exactly in the combined asymmetry $A_{1N}^{\pi^+ - \pi^-}$, the $s$-quark does not contribute, and we have:

$$A_{1p}^{\pi^+ - \pi^-} = \frac{\Delta \sigma_p^\pi^+ - \Delta \sigma_p^\pi^-}{\sigma_p^\pi^+ - \sigma_p^\pi^-} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v},$$
$$A_{1d}^{\pi^+ - \pi^-} = \frac{\Delta \sigma_d^\pi^+ - \Delta \sigma_d^\pi^-}{\sigma_d^\pi^+ - \sigma_d^\pi^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}.$$  

(2)

Therefore, measurements of $A_{1N}^{\pi^+ - \pi^-}$ on the proton and the deuteron can determine $\Delta u_v$ and $\Delta d_v$. On the other hand, the existing inclusive DIS data already constrains another non-singlet quantity:

$$g_1^p(x, Q^2) - g_1^n(x, Q^2) = \frac{1}{6} \left[ \left( \Delta u + \Delta \bar{u} \right) - \left( \Delta d + \Delta \bar{d} \right) \right]_{LO}.$$  

(3)

The polarized sea asymmetry can be extracted at leading order following:

$$(\Delta \bar{u} - \Delta \bar{d})_{LO} = 3(g_1^p - g_1^n)_{LO} - \frac{1}{2}(\Delta u_v - \Delta d_v)_{LO}.$$  

(4)
At the next-to-leading order, $x$ and $z$ are mixed through double convolutions, and instead of Eq. 1, we have:

$$\sigma^h(x, z) = \sum_f e_f^2 q_f \left[ 1 + \frac{\alpha_s}{2\pi} C_{qq} \right] D^h_q$$

$$+ \left( \sum_f e_f^2 q_f \right) \frac{\alpha_s}{2\pi} C_{qg} \otimes D^h_g + G \otimes \frac{\alpha_s}{2\pi} C_{gq} \otimes \left( \sum_f e_f^2 D^h_q \right).$$

(5)

and similarly for $\Delta\sigma^h$, where $C$s are well-known Wilson coefficients. The convolution terms become much simpler in quantities relate to $\sigma^{\pi^+} - \sigma^{\pi^-}$ since the $gq$ and $qg$ terms in Eq. 5 are identical for $\pi^+$ and $\pi^-$:

$$A_{1p}^{\pi^+ - \pi^-} = \frac{(4u_v - \Delta u_v) [1 + \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes] (D^+ - D^-)}{(4u_v - d_v) [1 + \frac{\alpha_s}{2\pi} C_{qq} \otimes] (D^+ - D^-)},$$

$$A_{1d}^{\pi^+ - \pi^-} = \frac{(\Delta u_v + d_v) [1 + \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes] (D^+ - D^-)}{(u_v + d_v) [1 + \frac{\alpha_s}{2\pi} C_{qq} \otimes] (D^+ - D^-)}.$$  

(6)

in which $\Delta u_v$ and $\Delta d_v$ evolve as non-singlets and do not mix with gluon and sea distributions. Once we extract $\Delta u_v$ and $\Delta d_v$ at next-to-leading order from Eq. 6, $\Delta \bar{u} - \Delta \bar{d}$ can be determined to next-to-leading order using the well-known NLO form of Eq. 3.

3. The Jefferson Lab experiment E04-113

Experiment E04-113 at Jefferson Lab Hall C is specifically designed to have well controlled phase spaces and hadron detection efficiencies such that the combined asymmetries $A_{1N}^{\pi^+ \pm \pi^-}$, in addition to the individual asymmetries $A_{1N}^{h \pi}$ ($h = \pi^+, \pi^-, K^+, K^-$), can be determined with high precision. The existing HMS spectrometer will be used as the hadron detector at 10.8° and a central momentum of 2.71 GeV/c, corresponding to $\langle z \rangle \approx 0.5$ to favor the current fragmentation. For the electron detector, a combination of a large calorimeter array and a gas Cherenkov will be used. The experiment will cover $0.12 < x < 0.41$ with $1.21 < Q^2 < 3.14$ (GeV/c)$^2$ and $2.31 < W < 3.09$ GeV.

In addition to the Christova-Leader method, the “fixed-$z$ purity” method of spin-flavor decomposition will be applied to provide a consistency check. At the well-defined $z$-value of this experiment, the “purity matrices” can be directly calculated based on unpolarized PDFs and the ratio of fragmentation functions, rather than from a Monte Carlo simulation which involves a fragmentation model. The expected statistical accuracies and the estimated systematic uncertainties are shown in Fig.1.
Figure 1. The expected statistical accuracies of experiment E04-113 for two independent methods of flavor decomposition (Christova-Leader and “fixed-$z$ purity”) are compared with the HERMES data\textsuperscript{1} and the SMC data\textsuperscript{4}. The open boxes represent the systematic uncertainties of the Christova-Leader method.

4. Conclusions

Experiment E04-113 at Jefferson Lab plans to extract quark polarizations based on the measurement of the combined asymmetries $A_{1N}^{+\pi^-\pi^+}$. The much improved statistics over the HERMES data will present us with the first opportunity to probe the possible flavor asymmetry of the light sea quark polarization.

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