The spin of the nucleon in the semi-inclusive DIS with charged current

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1 Introduction

The investigation of spin structure of the nucleon is one of the actual problems of particle physics [1]. According to recent experimental data [2]–[5]the quarks are responsible for 33-35% of nucleon spin and the strange quarks contribution is near to zero $\Delta s \sim 0.1$ The nucleon spin problem requires the further experimental research of all contributions. In present work the possibilities of determination of the quark contributions to the nucleon spin based on observable asymmetries of the semi-inclusive deep inelastic scattering (SIDIS) with the charged current are considered.

2 The semi-inclusive deep inelastic $lp-$ scattering

Let us consider the process of semi-inclusive deep inelastic $lp-$ scattering with charged weak current

$$\ell + p \to \nu + h + X. \tag{1}$$

The differential cross sections of the process (1) in the case of a lepton have the form

$$\sigma_{\ell^-} = 2\rho x \left\{ \sum_{q_i,q_j} q_i(x) D^h_{q_j}(z) + y_1^2 \sum_{\bar{q}_j,\bar{q}_i} \bar{q}_j(x) D^h_{\bar{q}_i}(z) + \right.$$

$$\left. + P_N \left(\sum_{q_i,q_j} \Delta q_i(x) D^h_{q_j}(z) - y_1^2 \sum_{\bar{q}_j,\bar{q}_i} \Delta \bar{q}_j(x) D^h_{\bar{q}_i}(z) \right) \right\}, \quad (2)$$

where $q = u, c, t$, $\bar{q} = \bar{d}, \bar{s}, \bar{b}$.

Here $\sigma \equiv \frac{d^3\sigma}{dxdydz}$, $\rho = \frac{G^2 s}{2\pi}\left(\frac{m_w^2}{m_w^2 + Q^2}\right)^2$, $y_1 = 1 - y$, G is Fermi constant, m_w is the W-boson mass, $x = \frac{Q^2}{2p\cdot q}$, $y = \frac{p\cdot q}{p\cdot k}$, $Q^2 = -q^2 = -(k-k')^2$, $s = 2p\cdot k$, $k(k')$ and p are the initial (final) lepton and proton 4-momenta, respectively, P_N is the degree of longitudinal polarization of proton, $q(x)(\Delta q(x))/\bar{q}(x)(\Delta\bar{q}(x))$ are the unpolarized (polarized) quark/antiquark distribution functions, $D^h_q(z)(D^h_{\bar{q}}(z))$ are the fragmentation functions of quark (antiquark) with flavor q to the hadron h.Similary we received the cross section in the case of antilepton.

We define the polarization asymmetries in the form of [6]

$$A^{h^+-h^-}_{\ell^-} = \frac{\left(\sigma^{\downarrow\uparrow}_{\ell^-}\right)^{h^+-h^-} - \left(\sigma^{\downarrow\downarrow}_{\ell^-}\right)^{h^+-h^-}}{\left(\sigma^{\downarrow\uparrow}_{\ell^-}\right)^{h^+-h^-} + \left(\sigma^{\downarrow\downarrow}_{\ell^-}\right)^{h^+-h^-}}, \quad (3)$$

$$A^{h^+-h^-}_{\ell^+} = \frac{\left(\sigma^{\uparrow\uparrow}_{\ell^+}\right)^{h^+-h^-} - \left(\sigma^{\uparrow\downarrow}_{\ell^+}\right)^{h^+-h^-}}{\left(\sigma^{\uparrow\uparrow}_{\ell^+}\right)^{h^+-h^-} + \left(\sigma^{\uparrow\downarrow}_{\ell^+}\right)^{h^+-h^-}}, \quad (4)$$

$$A^{h^+-h^-}_{\pm} = \frac{\left[\left(\sigma^{\downarrow\uparrow}_{\ell^-}\right)^{h^+-h^-} \pm \left(\sigma^{\uparrow\uparrow}_{\ell^+}\right)^{h^+-h^-}\right] - \left[\left(\sigma^{\downarrow\downarrow}_{\ell^-}\right)^{h^+-h^-} \pm \left(\sigma^{\uparrow\downarrow}_{\ell^+}\right)^{h^+-h^-}\right]}{\left[\left(\sigma^{\downarrow\uparrow}_{\ell^-}\right)^{h^+-h^-} \pm \left(\sigma^{\uparrow\uparrow}_{\ell^+}\right)^{h^+-h^-}\right] + \left[\left(\sigma^{\downarrow\downarrow}_{\ell^-}\right)^{h^+-h^-} \pm \left(\sigma^{\uparrow\downarrow}_{\ell^+}\right)^{h^+-h^-}\right]}, \quad (5)$$

where $\sigma^{h^+-h^-} = \sigma^{h^+} - \sigma^{h^-}$.

The first arrow corresponds to the helicity of the initial lepton (↓) or antilepton (↑) and the second – to the polarization degree of the proton: ↑ ($P_N = +1$), ↓ ($P_N = -1$).

Let us consider the case $h = \pi^+$.Equations (3),(4), (5) for the case of a proton targets for asymmetries give us

$$A_{\ell^-}^{\pi^+-\pi^-} = \frac{\Delta u(x) - y_1^2 \Delta \bar{d}(x)}{u(x) + y_1^2 \bar{d}(x)}, \tag{6}$$

$$A_{\ell^+}^{\pi^+-\pi^-} = \frac{y_1^2 \Delta d(x) - \Delta \bar{u}(x)}{y_1^2 d(x) + \bar{u}(x)}, \tag{7}$$

$$A_{+,p}^{\pi^+-\pi^-} = \frac{\Delta u(x) + \Delta \bar{u}(x) - y_1^2(\Delta d(x) + \Delta \bar{d}(x))}{u_V(x) - y_1^2 d_V(x)}, \tag{8}$$

$$A_{-,p}^{\pi^+-\pi^-} = \frac{\Delta u_V(x) + y_1^2 \Delta d_V(x)}{u(x) + \bar{u}(x) + y_1^2(d(x) + \bar{d}(x))}, \tag{9}$$

where

$$u_V(x) = u(x) - \bar{u}(x), d_V(x) = d(x) - \bar{d}(x).$$

It takes into account the correlations for $\pi-$ meson fragmentation functions [7],[8]

$$D_d^{\pi^+-\pi^-} = -D_u^{\pi^+-\pi^-}, \quad D_u^{\pi^+-\pi^-} = -D_{\bar{u}}^{\pi^+-\pi^-}$$

In the same way we receive asymmetries for the case $h = K^+$. For $K-$meson fragmentation function look like $D_d^{K^+-K^-} = 0$, hence the asymmetries (3)-(5) have the following form

$$A_{\ell^-}^{K^+-K^-} = -\frac{\Delta \bar{d}(x)}{\bar{d}(x)}, \tag{10}$$

$$A_{\ell^+}^{K^+-K^-} = \frac{\Delta d(x)}{d(x)}, \tag{11}$$

$$A_{+,p}^{K^+-K^-} = -\frac{\Delta d_V(x)}{d_V(x)}, \tag{12}$$

$$A_{-,p}^{K^+-K^-} = \frac{\Delta d_V(x)}{d(x) + \bar{d}(x)}, \tag{13}$$

where $\Delta d_V(x) = \Delta d(x) - \Delta \bar{d}(x)$.

For nucleon spin structure analysis we introduce the first moments of parton distributions as follows

$$\Delta q(\Delta\bar{q}) = \int_0^1 \Delta q(x)(\Delta\bar{q}(x))dx, \tag{14}$$

which correspond to the quark q(antiquark $\bar{q}$) contributions to the spin of nucleon.

Then the quark contributions to the nucleon spin can be defined from the asymmetries (10)–(13), (6), (7) as

$$\begin{aligned} \Delta d &= \int_0^1 d(x) A_{\ell+}^{K^+-K^-} dx, & (15) \\ \Delta\bar{d} &= -\int_0^1 \bar{d}(x) A_{\ell-}^{K^+-K^-} dx. & (16) \end{aligned}$$

$$\begin{aligned} \Delta u &= \int_0^1 \Big(A_{\ell-}^{\pi^+-\pi^-}(u(x) - y_1^2\bar{d}(x)) + y_1^2 A_{\ell-}^{K^+-K^-}\bar{d}(x)\Big)dx, & (17) \\ \Delta\bar{u} &= \int_0^1 \Big(-A_{\ell+}^{\pi^+-\pi^-}(y_1^2 d(x) + \bar{u}(x)) + y_1^2 A_{\ell+}^{K^+-K^-} d(x)\Big)dx. & (18) \end{aligned}$$

Valence $d-$, $u-$ quarks contribution can be determined from (9) and (13) as

$$\begin{aligned} \Delta d_V &= \int_0^1 d_V(x) A_{+,p}^{K^+-K^-} dx, & (19) \\ \Delta u_V &= \int_0^1 \Big(\Big(u(x) + \bar{u}(x) + y_1^2(d(x) + \bar{d}(x))\Big)A_{-,p}^{\pi^+-\pi^-} + \\ &\quad + y_1^2 d_V(x) A_{+,p}^{K^+-K^-}\Big)dx. & (20) \end{aligned}$$

Strange quarks contributions $(\Delta s + \Delta\bar{s})$ can be determined using the asymmetry $A_{+,p}^{\pi^+-\pi^-}$ (8) and additional observable quantities – axial charges a_3 and a_8 (see, for example,[9])

$$\begin{aligned} a_3 &= (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}), \\ a_8 &= (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s}), & (21) \\ \Delta s + \Delta\bar{s} &= \frac{1}{2(1-y_1^2)}\Big(2\int_0^1 A_{+,p}^{\pi^+-\pi^-}(u_V(x) - y_1^2 d_V(x))dx - \\ &\quad - a_3(1+y_1^2)\Big) - a_8. & (22) \end{aligned}$$

3 The semi-inclusive neutrino DIS

A similar scheme for obtaining the quark flavours contributions in the case of the semi-inclusive neutrino DIS on the polarized deuteron targets

$$\nu(\bar{\nu}) + N \to \ell^-(\ell^+) + h + X. \tag{23}$$

For the π-mesons production in the case of a deuteron targets for asymmetry we have

$$A_{\nu d}^{\pi^+-\pi^-} = \frac{\Delta u(x) + \Delta d(x) - y_1^2(\Delta\bar{u}(x) + \Delta\bar{d}(x))}{u(x) + d(x) + y_1^2(\bar{u}(x) + \bar{d}(x))}(1 - 1.5\omega), \tag{24}$$

$$A_{\bar{\nu} d}^{\pi^+-\pi^-} = \frac{y_1^2(\Delta u(x) + \Delta d(x)) - (\Delta\bar{u}(x) + \Delta\bar{d}(x))}{y_1^2(u(x) + d(x)) + (\bar{u}(x) + \bar{d}(x))}(1 - 1.5\omega). \tag{25}$$

where $\omega = 0.05$ is a probability of $D-$ states of the wave function of the deutron. The quark contributions $\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$, $(\Delta s + \Delta\bar{s})$ can be determined using the asymmetry and additional observable quantities– axial charges a_3 and a_8

$$\begin{aligned}\Delta u + \Delta\bar{u} = &\frac{1}{4(1 - y_1^2)(1 - 1.5\omega)}\Big(\int_0^1 (A_{\nu d}^{\pi^+-\pi^-}(u(x) + d(x) + \\ &+ y_1^2(\bar{u}(x) + \bar{d}(x))) - A_{\bar{\nu} d}^{\pi^+-\pi^-}(y_1^2(u(x) + d(x)) + \bar{u}(x) + \\ &+ \bar{d}(x)))dx + a_3\Big),\end{aligned} \tag{26}$$

$$\begin{aligned}\Delta d + \Delta\bar{d} = &\frac{1}{4(1 - y_1^2)(1 - 1.5\omega)}\Big(\int_0^1 A_{\nu d}^{\pi^+-\pi^-}(u(x) + d(x) + \\ &+ y_1^2(\bar{u}(x) + \bar{d}(x))) - A_{\bar{\nu} d}^{\pi^+-\pi^-}(y_1^2(u(x) + d(x)) + \bar{u}(x) + \\ &+ \bar{d}(x)))dx - a_3\Big),\end{aligned} \tag{27}$$

$$\begin{aligned}\Delta s + \Delta\bar{s} = &\frac{1}{4(1 - y_1^2)(1 - 1.5\omega)}\Big(\int_0^1 A_{\nu d}^{\pi^+-\pi^-}(u(x) + d(x) + \\ &+ y_1^2(\bar{u}(x) + \bar{d}(x))) - A_{\bar{\nu} d}^{\pi^+-\pi^-}(y_1^2(u(x) + d(x)) + \bar{u}(x) + \\ &+ \bar{d}(x)))dx - a_8\Big).\end{aligned} \tag{28}$$

In the case of $K-$ mesons production we have asymmetries

$$A_{\nu d}^{K^+-K^-} = \frac{\Delta u(x) + \Delta d(x)}{u(x) + d(x)}(1 - 1.5\omega), \tag{29}$$

$$A_{\bar{\nu} d}^{K^+-K^-} = -\frac{\Delta \bar{u}(x) + \Delta \bar{d}(x)}{\bar{u}(x) + \bar{d}(x)}(1 - 1.5\omega). \tag{30}$$

Then using (29), (30) and (21) the quarks contribution is

$$\begin{aligned}\Delta u + \Delta \bar{u} &= \frac{1}{2(1-1.5\omega)}\left(\int_0^1 \Big[A_{\nu d}^{K^+-K^-}(u(x)+d(x)) - \right. \\ &\left. -A_{\bar{\nu} d}^{K^+-K^-}(\bar{u}(x)+\bar{d}(x)\Big]dx + a_3\right), \end{aligned}\tag{31}$$

$$\begin{aligned}\Delta d + \Delta \bar{d} &= \frac{1}{2(1-1.5\omega)}\left(\int_0^1 \Big[A_{\nu d}^{K^+-K^-}(u(x)+d(x)) - \right. \\ &\left. -A_{\bar{\nu} d}^{K^+-K^-}(\bar{u}(x)+\bar{d}(x))\Big]dx - a_3\right), \end{aligned}\tag{32}$$

$$\begin{aligned}\Delta s + \Delta \bar{s} &= \frac{1}{2(1-1.5\omega)}\left(\int_0^1 \Big[A_{\nu d}^{K^+-K^-}(u(x)+d(x)) - \right. \\ &\left. -A_{\bar{\nu} d}^{K^+-K^-}(\bar{u}(x)+\bar{d}(x))\Big]dx - a_8\right). \end{aligned}\tag{33}$$

The total valence $d-$, $u-$ quarks contribution can be determined from (29) and (30) as

$$\begin{aligned}\Delta u_V + \Delta d_V &= \frac{1}{(1-1.5\omega)}\left(\int_0^1 \Big[A_{\bar{\nu} d}^{K^+-K^-}(\bar{u}(x)+\bar{d}(x)) + \right. \\ &\left. +A_{\nu d}^{K^+-K^-}(u(x)+d(x))\Big]dx\right), \end{aligned}\tag{34}$$

4 Conclusions

1. Contributions of quark flavors are expressed via measurable asymmetries.The polarization asymmetries for the $\pi-$, $K-$ meson production in SIDIS with charged current do not depend from the fragmentation functions.

2.Spin asymmetries are determined for the case of $\pi-$, $K-$ meson production in semi-inclusive $\ell N-$ DIS and $\nu N-$ DIS. The obtained asymmetries do not depend on fragmentation functions.

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