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The strange-sea quark spin distribution in the nucleon from inclusive and semi-inclusive deep-inelastic scattering

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ABSTRACT

We propose new method which allows determination of the strange-sea quark spin distribution in the nucleon through measurement of various inclusive and semi-inclusive polarized deep inelastic electron–proton or muon–proton reactions. It is shown, that using combinations of inclusive data and semi-inclusive data containing neutral pions in the final state, it is possible to extract the strange-sea quark spin distribution. Similar result can be obtained for charged pions and some other hadrons also.

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The standard parton model (see, for instance [1,2]) allows to study spin structure of nucleons using both inclusive and semi-inclusive polarized deep-inelastic scattering (DIS) of leptons on nucleons. According to this model, an incoming electron or muon emits a spacelike virtual photon, which is absorbed by a quark in the nucleon. The nucleon is broken up, and the struck quark and the target remnant fragment into hadrons in the final state. The pioneering experiments to study the spin structure of the nucleon performed at SLAC [3,4] were measurements of inclusive spin asymmetries, in which, in final state, only the scattered lepton is observed. More precise later experiments (see, for instance [5]) showed that only a fraction of the nucleon spin can be attributed to the quark spins and that the strange quark sea seems to be negatively polarized [6]. The polarized semi-inclusive DIS with detection of one hadron in the final state adds important information on the scattering process. At present there are many theoretical and experimental efforts devoted to the study of the valence and sea quarks spin distributions in the nucleon. Here we are interested in the study of the strange-sea quark spin distribution. This point was already investigated earlier. Two different methods for the extraction of strange-sea quark spin distribution were proposed [7,8]. One of them was applied to the experimental data [8–10].

The objective of this Letter is to propose new method for the extraction, which, in our opinion, is simpler than preceding methods and, what is more important, allows to extract the same information using other set of experimental semi-inclusive DIS data. Together with the other available methods, it can be used by experimentalists for more detailed investigation of the subject.

Let us consider at first the inclusive DIS of lepton on proton $l_i + p \rightarrow l_f + X$, where $l_i(l_f)$ are initial (final) leptons, p is a proton and X is undetected state. Reaction can be wrote directly for intermediate virtual photon, as $\gamma^* + p \rightarrow X$. We are interested the

number of inclusive DIS events N^{inc} produced in a given bin of Bjorken variable $x = Q^2/2M_p\nu$, where $q^2 = -Q^2$ and ν are the square of the four-momentum and energy of the virtual photon, M_p is the proton mass, in configurations where the virtual photon and target proton helicities are antiparallel ($\uparrow\downarrow$) or parallel ($\uparrow\uparrow$). The standard parton model consideration [1,2] gives, up to constant factor:

$$N_{\uparrow\downarrow}^{\text{inc}} \sim \frac{4}{9}u_+(x) + \frac{4}{9}\bar{u}_+(x) + \frac{1}{9}d_+(x) + \frac{1}{9}\bar{d}_+(x) + \frac{1}{9}s_+(x) + \frac{1}{9}\bar{s}_+(x), \quad (1)$$

$$N_{\uparrow\uparrow}^{\text{inc}} \sim \frac{4}{9}u_-(x) + \frac{4}{9}\bar{u}_-(x) + \frac{1}{9}d_-(x) + \frac{1}{9}\bar{d}_-(x) + \frac{1}{9}s_-(x) + \frac{1}{9}\bar{s}_-(x), \quad (2)$$

where $q_+(q_-)$ denotes distribution function of a quark q with helicity parallel (antiparallel) to the proton helicity.

Now let us turn to the semi-inclusive DIS reaction with detection in final state π^0 meson in coincidence with the scattered lepton $l_i + p \rightarrow l_f + \pi^0 + X$, or for intermediate virtual photon, as $\gamma^* + p \rightarrow \pi^0 + X$. We will consider the number of π^0 mesons N^{π^0} produced in a given bin of variable x and z ($z = E_h/\nu$, where E_h is the final pion energy in lab. system), which is the fraction of the virtual photon energy taken by the pion, in configuration where the virtual photon and target proton helicities are antiparallel ($\uparrow\downarrow$) or parallel ($\uparrow\uparrow$). The standard parton model consideration [1,2] gives, up to constant factor:

$$N_{\uparrow\downarrow}^{\pi^0} \sim \frac{4}{9}u_+(x)D_u^{\pi^0}(z) + \frac{4}{9}\bar{u}_+(x)D_{\bar{u}}^{\pi^0}(z) + \frac{1}{9}d_+(x)D_d^{\pi^0}(z) + \frac{1}{9}\bar{d}_+(x)D_{\bar{d}}^{\pi^0}(z) + \frac{1}{9}s_+(x)D_s^{\pi^0}(z) + \frac{1}{9}\bar{s}_+(x)D_{\bar{s}}^{\pi^0}(z), \quad (3)$$

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$$\begin{aligned}
N_{\uparrow\uparrow}^{\pi^0} &\sim \frac{4}{9}u_-(x)D_u^{\pi^0}(z) + \frac{4}{9}\bar{u}_-(x)D_{\bar{u}}^{\pi^0}(z) \\
&+ \frac{1}{9}d_-(x)D_d^{\pi^0}(z) + \frac{1}{9}\bar{d}_-(x)D_{\bar{d}}^{\pi^0}(z) \\
&+ \frac{1}{9}s_-(x)D_s^{\pi^0}(z) + \frac{1}{9}\bar{s}_-(x)D_{\bar{s}}^{\pi^0}(z), \quad (4)
\end{aligned}$$

where $D_q^h(z)$ is the fragmentation function of a quark q into the hadron h with energy $E_h = z \cdot \nu$. We will follow the notations and approximations for fragmentation functions, which were used in [7]. The above relations have been obtained with the standard assumption that the fragmentation function $D_q^h(z)$ does not depend on the quark helicity, i.e., that $D_{q+}^h(z) = D_{q-}^h(z)$. Now we may use the isospin and charge conjugation symmetry to relate various fragmentation functions, so finally we are left, for case of charged pions, with three independent fragmentation functions $D_1(z)$, $D_2(z)$ and $D_3(z)$, called favoured, unfavoured and strange quark fragmentation functions, correspondingly.

$$D_1(z) \equiv D_u^{\pi^+}(z) = D_u^{\pi^-}(z) = D_d^{\pi^-}(z) = D_d^{\pi^+}(z), \quad (5)$$

$$D_2(z) \equiv D_u^{\pi^-}(z) = D_u^{\pi^+}(z) = D_d^{\pi^+}(z) = D_d^{\pi^-}(z), \quad (6)$$

$$D_3(z) \equiv D_s^{\pi^+}(z) = D_s^{\pi^-}(z) = D_{\bar{s}}^{\pi^-}(z) = D_{\bar{s}}^{\pi^+}(z). \quad (7)$$

In case of neutral pion situation is simpler, because the wave function of the π^0 meson is:

$$\pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}, \quad (8)$$

and we are left with two fragmentation functions $D_0(z) = D_1(z) + D_2(z)$ and $D_3(z)$.

$$\frac{1}{2}D_0(z) \equiv D_u^{\pi^0}(z) = D_{\bar{u}}^{\pi^0}(z) = D_d^{\pi^0}(z) = D_{\bar{d}}^{\pi^0}(z), \quad (9)$$

$$D_3(z) \equiv D_s^{\pi^0}(z) = D_{\bar{s}}^{\pi^0}(z). \quad (10)$$

In this notations, Eqs. (3) and (4) take the form

$$\begin{aligned}
N_{\uparrow\downarrow}^{\pi^0} &\sim \left[\frac{4}{9}u_+(x) + \frac{4}{9}\bar{u}_+(x) + \frac{1}{9}d_+(x) + \frac{1}{9}\bar{d}_+(x) \right] \frac{1}{2}D_0(z) \\
&+ \left[\frac{1}{9}s_+(x) + \frac{1}{9}\bar{s}_+(x) \right] D_3(z), \quad (11)
\end{aligned}$$

$$\begin{aligned}
N_{\uparrow\uparrow}^{\pi^0} &\sim \left[\frac{4}{9}u_-(x) + \frac{4}{9}\bar{u}_-(x) + \frac{1}{9}d_-(x) + \frac{1}{9}\bar{d}_-(x) \right] \frac{1}{2}D_0(z) \\
&+ \left[\frac{1}{9}s_-(x) + \frac{1}{9}\bar{s}_-(x) \right] D_3(z). \quad (12)
\end{aligned}$$

It is convenient instead of $q_+(x)$ and $q_-(x)$ introduce the standard quark distribution functions $q(x)$ and $\Delta q(x)$:

$$q(x) \equiv q_+(x) + q_-(x), \quad \Delta q(x) \equiv q_+(x) - q_-(x). \quad (13)$$

Then from Eqs. (1), (2) and (11), (12) follows:

$$\begin{aligned}
N_{\uparrow\downarrow}^{\text{inc}} - N_{\uparrow\uparrow}^{\text{inc}} &\sim \frac{4}{9}\Delta u(x) + \frac{4}{9}\Delta \bar{u}(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta \bar{d}(x) \\
&+ \frac{1}{9}\Delta s(x) + \frac{1}{9}\Delta \bar{s}(x), \quad (14)
\end{aligned}$$

$$\begin{aligned}
N_{\uparrow\downarrow}^{\text{inc}} + N_{\uparrow\uparrow}^{\text{inc}} &\sim \frac{4}{9}u(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}d(x) + \frac{1}{9}\bar{d}(x) \\
&+ \frac{1}{9}s(x) + \frac{1}{9}\bar{s}(x), \quad (15)
\end{aligned}$$

$$\begin{aligned}
N_{\uparrow\downarrow}^{\pi^0} - N_{\uparrow\uparrow}^{\pi^0} &\sim \left[\frac{4}{9}\Delta u(x) + \frac{4}{9}\Delta \bar{u}(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta \bar{d}(x) \right] \frac{1}{2}D_0(z) \\
&+ \left[\frac{1}{9}\Delta s(x) + \frac{1}{9}\Delta \bar{s}(x) \right] D_3(z), \quad (16)
\end{aligned}$$

$$\begin{aligned}
N_{\uparrow\downarrow}^{\pi^0} + N_{\uparrow\uparrow}^{\pi^0} &\sim \left[\frac{4}{9}u(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}d(x) + \frac{1}{9}\bar{d}(x) \right] \frac{1}{2}D_0(z) \\
&+ \left[\frac{1}{9}s(x) + \frac{1}{9}\bar{s}(x) \right] D_3(z). \quad (17)
\end{aligned}$$

Now we can obtain expressions for strange sea polarization, using two ways.

First way includes combinations of inclusive and semi-inclusive data. From Eqs. (14)–(17) we obtain for strange sea polarization:

$$\frac{\Delta s(x) + \Delta \bar{s}(x)}{s(x) + \bar{s}(x)} = \frac{N_{\uparrow\downarrow}^{\pi^0} - N_{\uparrow\uparrow}^{\pi^0} - \frac{1}{2}D_0(z)(N_{\uparrow\downarrow}^{\text{inc}} - N_{\uparrow\uparrow}^{\text{inc}})}{N_{\uparrow\downarrow}^{\pi^0} + N_{\uparrow\uparrow}^{\pi^0} - \frac{1}{2}D_0(z)(N_{\uparrow\downarrow}^{\text{inc}} + N_{\uparrow\uparrow}^{\text{inc}})}. \quad (18)$$

For increasing of statistics it is desirable take semi-inclusive data in maximal wide region of z , $z_{\min} < z < z_{\max}$, then instead of fragmentation function $D_0(z)$ one need to take integral from it over z . Eq. (18) can be written in the simple form $(1-r)/(1+r)$, where $r = (N_{\uparrow\uparrow}^{\pi^0} - \frac{1}{2}D_0(z)N_{\uparrow\uparrow}^{\text{inc}})/(N_{\uparrow\downarrow}^{\pi^0} - \frac{1}{2}D_0(z)N_{\uparrow\downarrow}^{\text{inc}})$.

Second way includes semi-inclusive π^0 meson production data only and can be expressed in form:

$$\frac{\Delta s(x) + \Delta \bar{s}(x)}{s(x) + \bar{s}(x)} = \frac{(N_{\uparrow\downarrow}^{\pi^0} - N_{\uparrow\uparrow}^{\pi^0})_1 - R_{12}(N_{\uparrow\downarrow}^{\pi^0} - N_{\uparrow\uparrow}^{\pi^0})_2}{(N_{\uparrow\downarrow}^{\pi^0} + N_{\uparrow\uparrow}^{\pi^0})_1 - R_{12}(N_{\uparrow\downarrow}^{\pi^0} + N_{\uparrow\uparrow}^{\pi^0})_2}, \quad (19)$$

where $(N_{\uparrow\downarrow}^{\pi^0} \pm N_{\uparrow\uparrow}^{\pi^0})_1$ ($(N_{\uparrow\downarrow}^{\pi^0} \pm N_{\uparrow\uparrow}^{\pi^0})_2$) means, that corresponding data taken in region z_1 (z_2). Here z_1 and z_2 are two different bins on z . It is desirable to take them maximal large as was discussed above. Factor R_{12} is a ratio of fragmentation functions in different regions of z $R_{12} = D_0(z_1)/D_0(z_2)$. Eq. (19) also can be written in the form $(1-r)/(1+r)$, with $r = (N_{\uparrow\uparrow}^{\pi^0} - N_{\uparrow\downarrow}^{\pi^0}R_{12})/(N_{\uparrow\downarrow}^{\pi^0} - N_{\uparrow\uparrow}^{\pi^0}R_{12})$.

The above consideration can be repeated for combination of charged pions ($\pi^\pm \equiv \pi^+ + \pi^-$), which finally gives instead of Eqs. (18) and (19) similar equations for charged pions:

$$\frac{\Delta s(x) + \Delta \bar{s}(x)}{s(x) + \bar{s}(x)} = \frac{N_{\uparrow\downarrow}^{\pi^\pm} - N_{\uparrow\uparrow}^{\pi^\pm} - D_0(z)(N_{\uparrow\downarrow}^{\text{inc}} - N_{\uparrow\uparrow}^{\text{inc}})}{N_{\uparrow\downarrow}^{\pi^\pm} + N_{\uparrow\uparrow}^{\pi^\pm} - D_0(z)(N_{\uparrow\downarrow}^{\text{inc}} + N_{\uparrow\uparrow}^{\text{inc}})}, \quad (20)$$

$$\frac{\Delta s(x) + \Delta \bar{s}(x)}{s(x) + \bar{s}(x)} = \frac{(N_{\uparrow\downarrow}^{\pi^\pm} - N_{\uparrow\uparrow}^{\pi^\pm})_1 - R_{12}(N_{\uparrow\downarrow}^{\pi^\pm} - N_{\uparrow\uparrow}^{\pi^\pm})_2}{(N_{\uparrow\downarrow}^{\pi^\pm} + N_{\uparrow\uparrow}^{\pi^\pm})_1 - R_{12}(N_{\uparrow\downarrow}^{\pi^\pm} + N_{\uparrow\uparrow}^{\pi^\pm})_2}. \quad (21)$$

Let us briefly discuss Eqs. (18)–(21), which are main results of this study. Eq. (18) contains two combinations of inclusive as well as semi-inclusive DIS polarized events and the combination of the so-called favoured and unfavoured fragmentation functions. The events can be obtained from the same measurement. Fragmentation functions can be obtained from DIS on nucleon or from e^+e^- annihilation. Eq. (19) contains only two combinations of semi-inclusive DIS polarized events and the ratio of fragmentation functions measured in different bins of z . In our opinion, this structure leads to the reduction of systematic errors in Eq. (19) in comparison with Eq. (18) and consequently gives it some advantage. Eqs. (20) and (21) can be used instead of Eqs. (18) and (19) if arise problems with statistics.

It is interesting to compare Eq. (20) of this Letter with another method for determination of the strange sea spin distribution available in literature. We have in view the Eq. (18) from Ref. [7]. Formula (18) in [7] consists of the ratios of polarized cross sections and asymmetries, while formula (20) in this work consists of the numbers of polarized inclusive and semi-inclusive events. It is main difference between these methods. The structure of Eq. (20) is simpler than one of Eq. (18) from [7]. It will be very useful to measure the strange sea spin distribution by these two alternative methods and to compare results.

The scheme developed above for pions can be applied, without any change, for the consideration of ρ^0 mesons in final state also. Diffractive ρ^0 mesons can be rejected if to exclude from consideration values of variable z close to the unity. If to suppose that ϕ meson is pure $s\bar{s}$ state, then expressions of type Eqs. (18) and (19) can be obtained for ϕ meson by changing:

$$\pi^0 \rightarrow \phi, \quad \frac{1}{2}D_0(z) \rightarrow D_u^\phi(z), \quad (22)$$

where $D_u^\phi(z)$ is the fragmentation function for the u -quark to turn into ϕ meson, and it is supposed also that $D_u^\phi(z) = D_d^\phi(z) = D_{\bar{u}}^\phi(z) = D_{\bar{d}}^\phi(z)$. Our final results (Eqs. (18)–(21)) do not depend from the type of target and can be applied in the same form for neutron and deuteron targets also. Now let us discuss the kinematic region where above formulae are applicable. The part of its time in order of $1/xM_p$ the virtual photon behaves as a quark–antiquark pair. If this time is essentially larger than the size of proton then instead of the photon with target will interact quark–antiquark pair. We can escape this situation imposing the restriction $x > 0.1$. Another restriction is connected with the fact that our consideration is applicable only for hadrons belonging to the current fragmentation region. These hadrons is convenient to pick out by means of Feynman variable $x_F \approx 2p_{\parallel}^*/W$, where p_{\parallel}^* is the longitudinal momentum of the hadron with respect to the virtual photon in the photon–nucleon center of mass frame, W is the invariant mass of the virtual photon–nucleon system. At high energies (ν on the order to 100 GeV) the condition $x_F > 0$ is enough

for separation of the current fragmentation region. At moderate energies (ν on the order to 10 GeV) situation is more complicated, because current and target fragmentation regions do not clearly separated. For this energy region can be recommended that each hadron has a minimum z of 0.2 and x_F of 0.1. In order to exclude effects from nucleon resonances as well as to improve the separation between the current and target fragmentation regions it is desirable to impose the additional requirement $W^2 \geq 10 \text{ GeV}^2$ (such condition uses HERMES experiment). As a last remark, one should note that the experimental realization of this scheme can be performed by HERMES experiment at DESY, the COMPASS Collaboration, EMC's successor at CERN and at JLAB after beam-energy upgrade.

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