The $x$-dependent helicity distributions for valence quarks in nucleons

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Abstract

We derive simple relations between the polarized and unpolarized valence quark distributions in a light-cone SU(6) quark-spectator model for nucleons. The explicit $x$-dependent Wigner rotation effect for the light-flavor quarks is calculated. It is shown that the mass difference between the scalar and vector spectators could reproduce the up and down valence quark asymmetry that accounts for the observed ratio $F_n^2/F_p^2$. The proton, neutron, and deuteron polarization asymmetries, $A_p^1$, $A_n^1$, and $A_d^1$, are in agreement with the available data by taking into account the Wigner rotation effect. The calculated $x$-dependent helicity distributions of the up and down valence quarks are compared with the recent results from semi-inclusive hadron asymmetries in polarized deep inelastic scattering by the

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Spin Muon Collaboration.
The observation of the Ellis-Jaffe sum rule (EJSR) violation in the inclusive polarized deep inelastic scattering experiments at CERN [1, 2] and SLAC [3, 4] has received an extensive attention on the spin content of nucleons. The experimental data of the integrated spin-dependent structure functions for the nucleons are generally understood to imply that the sum of the up, down, and strange quark helicities in the nucleon is much smaller than the nucleon spin [5]. There has been a number of possible interpretations [6] for the EJSR violation, and the quark helicity distributions for each flavor are quite different in these interpretations. It is clear that precise experimental measurements about the explicit quark helicity distributions for each flavor will be of crucial importance to test various interpretations of the EJSR violation.

The semi-inclusive processes in polarized deep inelastic scattering have been proposed to provide further informations about the helicity distributions for different quark flavors [7, 8, 9, 10]. The measurements of the helicity distributions for the valence up (u) and down (d) quarks from semi-inclusive hadron charge asymmetries in polarized deep inelastic scattering have been taken by the Spin Muon Collaboration (SMC) recently [11, 12]. The progress in experiments requires improved theoretical calculations of each flavor valence and sea quark helicity distributions that can be measured in future experiments. There have been attempts to calculate the quark helicity distributions for each flavor from general QCD arguments in
light-cone formalism \cite{13}, by assuming simple relations with the unpolarized quark distributions \cite{14}, or from parametrizations \cite{15}. The purpose of this paper is to investigate the quark helicity distributions for the valence u and d quarks in a light-cone SU(6) quark-spectator model for nucleons. We derive simple relations between polarized and unpolarized valence quark distributions by taking into account the explicit flavor asymmetry due to the difference between the scalar and vector spectators and the Wigner rotation effect due to the internal quark transversal motions \cite{3, 16, 17, 18}.

The deep inelastic lepton nucleon scattering is well described by the impulse approximation picture of the quark-parton model \cite{19, 20, 21} in which the incident lepton scatters incoherently off a parton in the nucleon with the remaining nucleon constituents treated as a quasi-particle spectator. From this picture one can calculate the valence quark distributions in the quark-diquark model where the single valence quark is the scattered parton and the non-interacting diquark serves to provide the quantum number of the spectator \cite{22, 23, 24}. The proton wave function in the quark-diquark model \cite{25} is written as

\begin{equation}
\Psi_{p}^{\uparrow\downarrow}(qD) = \sin \theta \varphi_{V} |qV >^{\uparrow\downarrow} + \cos \theta \varphi_{S} |qS >^{\uparrow\downarrow},
\end{equation}

with

\begin{align}
|qV >^{\uparrow\downarrow} &= \pm \frac{1}{3}[V_{0}(ud)u^{\uparrow\downarrow} - \sqrt{2}V_{\pm 1}(ud)u^{\downarrow\uparrow} - \sqrt{2}V_{0}(uu)d^{\downarrow\uparrow} + 2V_{\pm 1}(uu)d^{\uparrow\downarrow}]; \\
|qS >^{\uparrow\downarrow} &= S(ud)u^{\uparrow\downarrow},
\end{align}

(2)
where $V_s(q_1q_2)$ stays for a $q_1q_2$ vector diquark Fock state with third spin component $s_z$, $S(ud)$ stays for a $ud$ scalar diquark Fock state, $\varphi_D$ stays for the momentum space wave function of the quark-diquark with $D$ representing the vector ($V$) or scalar ($S$) diquarks, and $\theta$ is a mixing angle that breaks SU(6) symmetry at $\theta \neq \pi/4$. In this paper we choose the bulk SU(6) symmetry case $\theta = \pi/4$. From Eq. (1) we get the unpolarized quark distributions

$$u_v(x) = \frac{1}{2} a_S(x) + \frac{1}{6} a_V(x);$$

$$d_v(x) = \frac{1}{3} a_V(x),$$

where $a_D(x)$ ($D = S$ or $V$) is normalized such that $\int_0^1 dx a_D(x) = 3$ and $a_D(x)$ denotes the amplitude for the quark $q$ is scattered while the spectator is in the diquark state $D$. Therefore we can write, by assuming the isospin symmetry between the proton and the neutron, the unpolarized structure functions for nucleons,

$$F_2^p(x) = xs(x) + \frac{2}{3} x a_S(x) + \frac{1}{3} x a_V(x);$$

$$F_2^n(x) = xs(x) + \frac{1}{18} x a_S(x) + \frac{1}{6} x a_V(x),$$

where $s(x)$ denotes the contribution from the sea.

Exact SU(6) symmetry provides the relation $a_S(x) = a_V(x)$ which implies the valence flavor symmetry $u_v(x) = 2d_v(x)$. This gives the prediction $F_2^n(x)/F_2^p(x) \geq 2/3$ for all $x$ and is ruled out by the experimental observation $F_2^n(x)/F_2^p(x) < 1/2$ for $x \to 1$. It has been a well established fact that the valence flavor symmetry $u_v(x) = 2d_v(x)$ does not hold and the
explicit $u_v(x)$ and $d_v(x)$ can be parameterized from the combined experimental data from deep inelastic scatterings of electron (muon) and neutrino (anti-neutrino) on the proton and the neutron et al.. In this sense, any theoretical calculation of quark distributions should reflect the flavor asymmetry between the valence $u$ and $d$ quarks in a reasonable picture. We will show in the following that the mass difference between the scalar and vector spectators can reproduce the up and down valence quark asymmetry that accounts for the observed ratio $F_2^n(x)/F_2^p(x)$ at large $x$.

From the well-known quark-parton model [19] we know that it is proper to describe deep inelastic scattering as the sum of incoherent scatterings of the incident lepton on the partons in the infinite momentum frame or in the light-cone formalism [20, 21]. In the Bjorken limit $Q^2 \to \infty$ and $\nu \to \infty$ with $x = Q^2/2M\nu$ ranging from 0 to 1, the amplitude for the quark $q$ is scattered while the spectator in the spin state $D$ can be written as

$$a_D(x) \propto \int [d^2k_\perp] |\varphi_D(x, k_\perp)|^2.$$  \hspace{1cm} (5)

We adopt the Brodsky-Huang-Lepage prescription [27] for the light-cone momentum space wave function of the quark-spectator

$$\varphi_D(x, k_\perp) = A_D \exp\left\{ -\frac{1}{8\beta_D^2} \left[ \frac{m_q^2 + k_\perp^2}{x} + \frac{m_D^2 + k_\perp^2}{1-x} \right] \right\},$$  \hspace{1cm} (6)

where $k_\perp$ is the internal quark transversal momentum, $m_q$ and $m_D$ are the masses for the quark $q$ and spectator $D$, and $\beta_D$ is the harmonic oscillator
scale parameter. The values of the parameters $\beta_D$, $m_q$ and $m_D$ can be adjusted by fitting the hadron properties such as the electromagnetic form factors, the mean charge radiuses, and the weak decay constants et al. in the relativistic light-cone quark model [28]. In this paper we simply adopt $m_q = 330$ MeV and $\beta_D = 330$ MeV as in the scale often adopted in literature [28]. The masses of the scalar and vector spectators should be different taking into account the spin force from color magnetism or alternatively from instantons [18]. We choose, e.g., $m_S = 600$ MeV and $m_V = 900$ MeV as estimated to explain the N-Δ mass difference. The mass difference between the scalar and vector spectators causes difference between $a_S(x)$ and $a_V(x)$, and the flavor asymmetry between the valence quark distribution functions $u_v(x)$ and $d_v(x)$ can thus manifest itself. In Fig. 1 we present the calculated ratio $F_2^n(x)/F_2^p(x)$ by neglecting the sea contribution $s(x)$. The calculated results are in reasonable agreement with the experimental data [29], at least for large $x$, and this supports the quark-spectator picture of deep inelastic scattering in which the difference between the scalar and vector spectators is important to reproduce the explicit SU(6) symmetry breaking while the bulk SU(6) symmetry of the quark model still holds. The above result is in agreement with the bag model result of the effect on the structure functions due to the mass difference between the spectator scalar and vector diquarks [30].

We now turn our attention to the polarized quark distributions. We
should take into account the contribution from the Wigner rotation which is one important ingredient in the quark-parton model and light-cone descriptions of polarized deep inelastic scattering [3, 13, 17, 18]. The quantity $\Delta q$ measured in polarized deep inelastic scattering is defined by the axial current matrix element

$$\Delta q = \langle p, \uparrow | \gamma^+ \gamma_5 q | p, \uparrow \rangle.$$  

(7)

In the light-cone or quark-parton descriptions, $\Delta q(x) = q^+(x) - q^-(x)$, where $q^+(x)$ and $q^-(x)$ are the probability of finding a quark or antiquark with longitudinal momentum fraction $x$ and polarization parallel or antiparallel to the proton helicity in the infinite momentum frame. However, in the proton rest frame, one finds,

$$\Delta q(x) = \int [d^2 k_\perp] W_D(x, k_\perp) [q_{s_z=\frac{1}{2}}(x, k_\perp) - q_{s_z=-\frac{1}{2}}(x, k_\perp)],$$  

(8)

with

$$W_D(x, k_\perp) = \frac{(k^+ + m)^2 - k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$  

(9)

being the contribution from the relativistic effect due to the quark transversal motions, $q_{s_z=\frac{1}{2}}(x, k_\perp)$ and $q_{s_z=-\frac{1}{2}}(x, k_\perp)$ being the probability of finding a quark and antiquark with rest mass $m$ and with spin parallel and antiparallel to the rest proton spin, and $k^+ = xM$ where $M = \frac{m_2^2 + k^2}{x} + \frac{m_1^2 + k^2}{1-x}$.

The Wigner rotation factor $W_D(x, k_\perp)$ ranges from 0 to 1; thus $\Delta q$ measured in polarized deep inelastic scattering cannot be identified with the spin carried by each quark flavor in the proton rest frame. This can be understood
from the fact that the vector sum of the constituent spins for a composite system is not Lorentz invariant by taking into account the relativistic effect from the Wigner rotation \[5\].

From Eq. (1) we get the spin distribution probabilities in the quark-diquark model

\[
\begin{align*}
    u^\uparrow_V &= \frac{1}{18}; \\
    u^\downarrow_V &= \frac{2}{18}; \\
    d^\uparrow_V &= \frac{1}{18}; \\
    d^\downarrow_V &= \frac{4}{18}; \\
    u^\uparrow_S &= \frac{1}{2}; \\
    u^\downarrow_S &= 0; \\
    d^\uparrow_S &= 0; \\
    d^\downarrow_S &= 0.
\end{align*}
\] (10)

From the above discussions about the Wigner rotation, we can write the quark helicity distributions for the u and d quarks

\[
\begin{align*}
    \Delta u_v(x) &= u^\uparrow_v(x) - u^\downarrow_v(x) = -\frac{1}{18} a_V(x) W_V(x) + \frac{1}{2} a_S(x) W_S(x); \\
    \Delta d_v(x) &= d^\uparrow_v(x) - d^\downarrow_v(x) = -\frac{1}{9} a_V(x) W_V(x),
\end{align*}
\] (11)

where \(W_D(x)\) is the correction factor due the Wigner rotation. From Eq. (3) one gets

\[
\begin{align*}
    a_S(x) &= 2u_v(x) - d_v(x); \\
    a_V(x) &= 3d_v(x).
\end{align*}
\] (12)

Combining Eqs. (11) and (12) we have

\[
\begin{align*}
    \Delta u_v(x) &= [u_v(x) - \frac{1}{2} d_v(x)] W_S(x) - \frac{1}{3} d_v(x) W_V(x); \\
    \Delta d_v(x) &= -\frac{1}{3} d_v(x) W_V(x).
\end{align*}
\] (13)

Thus we arrive at simple relations between the polarized and unpolarized quark distributions for the valence u and d quarks. We can calculate
the quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ from the unpolarized quark distributions $u_v(x)$ and $d_v(x)$ by relations (13), once the detailed $x$-dependent Wigner rotation factor $W_D(x)$ is known. On the other hand, we can also use relations (13) to study $W_S(x)$ and $W_V(x)$, once there are good quark distributions $u_v(x)$, $d_v(x)$, $\Delta u_v(x)$, and $\Delta d_v(x)$ from experiments. From another point of view, the relations (13) can be considered as the results of the conventional SU(6) quark model [22, 23, 24] by explicitly taking into account the Wigner rotation effect and the flavor asymmetry introduced by the mass difference between the scalar and vector spectators, thus any evidence for the invalidity of Eq. (13) will be useful to reveal new physics beyond the SU(6) quark model.

Encouraged by our above calculation of the valence u and d flavor asymmetry that accounts for the observed ratio $F_2^p(x)/F_2^n(x)$, we calculate the $x$-dependent Wigner rotation factor $W_D(x)$ in the light-cone SU(6) quark-spectator model by adopting the light-cone wave function Eq. (6). The calculated results are presented in Fig. 2 from which we notice the slight asymmetry between $W_S(x)$ (full curve) and $W_V(x)$ (dotted curve). Considering only the valence quark contributions, we can write the spin-dependent structure functions $g_1^p(x)$ and $g_1^n(x)$ for the proton and the neutron by

$$
\begin{align*}
g_1^p(x) &= \frac{1}{2} \left[ \frac{1}{9} \Delta u_v(x) + \frac{4}{9} \Delta d_v(x) \right] = \frac{1}{18} \left[ (4u_v(x) - 2d_v(x))W_S(x) - d_v(x)W_V(x) \right]; \\
g_1^n(x) &= \frac{1}{2} \left[ \frac{1}{9} \Delta u_v(x) + \frac{4}{9} \Delta d_v(x) \right] = \frac{1}{36} \left[ (2u_v(x) - d_v(x))W_S(x) - 3d_v(x)W_V(x) \right].
\end{align*}
$$

(14)
The proton, neutron, and deuteron polarization asymmetries, $A^p_1$, $A^n_1$, and $A^d_1$, are directly measured in experiments and are expressed by $A^N_1(x) = 2x g^N_1(x)/F^N_2(x)$, where $N$ denotes $p$, $n$, and $d$. We thus can adopt one set of existing unpolarized quark distribution parametrizations \(^{[11]}\) and the calculated $W_S(x)$ and $W_V(x)$ to calculate $A^N_1$. We present in Fig. 3 the calculated polarization asymmetries $A^N_1$ for the cases with asymmetric Wigner rotation ($W_V(x) \neq W_S(x)$) of fig.2 (full curves), no Wigner rotation ($W_S = W_V = 1$) (dotted curves), and large asymmetric Wigner rotation (dashed curves, see discussions below) respectively. We see that the calculated $A^N_1$ with Wigner rotation are in agreement with the experimental data, at least for $x \geq 0.1$. The large asymmetry between $W_S(x)$ and $W_V(x)$ has consequence for a better fit of the data.

As we consider only the valence quark contributions to $g^p_1(x)$ and $g^n_1(x)$, we should not expect to fit the Ellis-Jaffe sum data from experiments. This leaves room for additional contributions from sea quarks or other sources. We point out, however, it is possible to reproduce the observed Ellis-Jaffe sums $\Gamma^p_1 = \int_0^1 g^p_1(x) dx$ and $\Gamma^n_1 = \int_0^1 g^n_1(x) dx$ within the light-cone SU(6) quark-spectator model by introducing a large asymmetry between the Wigner rotation factors $W_S$ and $W_V$ for the scalar and vector spectators. For example, we need $\langle W_S \rangle = 0.56$ and $\langle W_V \rangle = 0.92$ to produce $\Gamma^p_1 = 0.136$ and $\Gamma^n_1 = -0.03$ as observed in experiments \(^{[2, 4]}\). This can be achieved by adopting a large difference between $\beta_S$ and $\beta_V$ which should be
adjusted by fitting other nucleon properties in the model [18]. The results of an example calculation of such kinds \( A_1^p(x), A_1^n(x), \) and \( A_1^d(x) \) are plotted (dashed curves) in Fig. 3 and the agreement with the data is good. This may suggest that the explicit SU(6) asymmetry could be also used to explain the EJSR violation (or partially) within a bulk SU(6) symmetry scheme of the quark model, or we take this as a hint for other SU(6) breaking source in additional to the SU(6) quark model. Of course, the magnitude of the SU(6) asymmetry or breaking should be constrained and estimated from considerations of other nucleon properties.

The validity of the results in this paper can be tested from experimental measurements of \( F_n^2(x)/F_p^2(x), d(x)/u(x), \) and \( \Delta d(x) \) near \( x \rightarrow 1. \) In this paper the dominant contribution to polarized and unpolarized quark distributions at large \( x \) is from \( u^v(x) \) due to the suppression of \( a_V(x) \) in comparison with \( a_S(x) \). This gives the prediction \( F_2^u(x)/F_2^p(x) = 1/4 \) for \( x \rightarrow 1 \) and is consistent with most parametrizations of unpolarized quark distributions. However, there is an alternative perturbative QCD expectation that the contribution from the u and d valence quarks are 5:1 at large \( x \) and this gives the prediction \( F_2^u(x)/F_2^p(x) = 3/7 \) for \( x \rightarrow 1 \) [13, 32]. It has been recently suggested [33] that the measured ratio \( F_2^n(x)/F_2^p(x) \) is consistent with this expectation after taking into account Fermi motion, binding and nucleon off-shell effects in the deuteron. This will be of crucial importance for later parametrizations of quark distributions, once this con-
clusion is confirmed. The ratio of neutrino and anti-neutrino cross sections on protons can provide further information about the ratio $d(x)/u(x)$ near $x = 1$ and test the two predictions of the quark model $(d(x)/u(x) \to 0)$ and the perturbative QCD $(d(x)/u(x) \to 1/5)$ \cite{34}, and this can avoid the uncertainties in the ratio $F_2^n(x)/F_2^p(x)$ due to the nuclear effect. However, the available experimental data \cite{35} are compatible with the two predictions and more precise data are needed for a clear distinction of the two cases.

We see from Eq. \cite{13} that $\Delta d(x) \leq 0$ in this paper, and this is in consistent with some other results \cite{14,15} and the quark model prediction $\Delta d(x)/d(x) \to -1/3$ near $x \to 1$ \cite{22,23,24,33}. The measurements of the explicit $x$-dependent quark helicity distributions for the valence $u$ and $d$ quarks have been taken by the Spin Muon Collaboration from semi-inclusive hadron charge asymmetries in polarized deep inelastic scattering \cite{11,12}. This will put constraints on the theoretical calculations of the quark helicity distributions for each flavor. In Fig. 4 we present our calculated quark helicity distributions $\Delta u_v(x)$ and $\Delta d_v(x)$ and compare them with the recent SMC data. The data are still not precise enough for making detailed comparison, but the agreement with $\Delta u_v(x)$ seems to be good. It seems that the agreement with $\Delta d_v(x)$ is poor and there is somewhat evidence for additional source of negative helicity contribution to the valence $d$ quark beyond the conventional quark model. Some progress have been made in this direction and will be given elsewhere \cite{36}. As in the case of the ratio
\[ \frac{F^u_2(x)}{F^d_2(x)} \text{ near } x \to 1, \]  
the quark model prediction \( \Delta d(x)/d(x) \to -1/3 \) is also different from the perturbative QCD prediction \( \Delta d(x)/d(x) \to 1 \) at large \( x \) and the available SMC data are still not possible to make a clear distinction between the two predictions.

Similar to the \( x \to 1 \) behaviors, the \( x \to 0 \) behaviors for the bulk SU(6) quark model results in this paper and the perturbative QCD expectation are also different. In the quark model consideration of this paper, the valence quarks provide the quantum number of the nucleons, thus it is difficult to expect \( q^u_v(x) = q^d_v(x) \) for the valence quarks at \( x = 0 \) without introducing large bulk SU(6) breaking mechanism. However, in the perturbative QCD consideration one expects \( q^u(x) - q^d(x) \to 0 \) near \( x \to 0 \) corresponding to the fact that long range correlations disappear for large rapidity separation and the unpolarized and polarized valence quark distributions have different Regge behavior at \( x = 0 \). Therefore the \( x \to 0 \) behaviors of the helicity distributions for the valence \( u \) and \( d \) quarks are also important to distinguish between the quark model and perturbative QCD predictions, as in the case of the \( x \to 1 \) behaviors of \( F^u_2(x)/F^d_2(x) \), \( d(x)/u(x) \) and \( \Delta d(x)/d(x) \). From above discussions, improved precision in experiments in the \( x \to 1 \) and \( x \to 0 \) end-point regions are highly needed for extracting clear information of the quark flavor and helicity distributions and revealing more about the explicit quark structure of nucleons.

In summary, we derived in this paper simple relations between the polar-
ized and unpolarized quark distributions for the valence up and down quarks in a light-cone SU(6) quark-spectator model for nucleons. The explicit $x$-dependent Wigner rotation effect for the light-flavor quarks is calculated. It is shown that the mass difference between the scalar and vector spectators could reproduce the up and down valence quark asymmetry that accounts for the observed ratio $F_2^n / F_2^p$. The calculated proton, neutron, and deuteron polarization asymmetries, $A_1^p$, $A_1^n$, and $A_1^d$, are in agreement with the available data by taking into account the Wigner rotation effect. The calculated $x$-dependent helicity distributions of the up and down valence quarks are compared with the recent results from semi-inclusive hadron asymmetries in polarized deep inelastic scattering by the Spin Muon Collaboration.

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Figure Captions

Fig. 1. The ratio $F_2^p/F_2^n$ as a function of the Bjorken scaling variable $x$. The curve is the calculated result in this work and the data (●) are from the revised NMC measurement [29].

Fig. 2. The $x$-dependent Wigner rotation factor $W_D(x)$ in the light-cone SU(6) quark-spectator model. The full and dotted curves are the calculated $W_S(x)$ and $W_V(x)$ in this work.

Fig. 3. The spin asymmetries $A_1^N(x)$ (a) for the proton, (b) for the neutron, and (c) for the deuteron as functions of the Bjorken scaling variable $x$. The curves are the calculated $A_1^N(x)$ in the light-cone SU(6) quark-spectator model with the Glück-Reya-Vogt (GRV) LO set of the unpolarized quark distribution parametrizations. The full curves are the results for slight asymmetric Wigner rotation factors $W_S(x)$ and $W_V(x)$ of fig.2; the dotted curves are the results without Wigner rotation ($W_V = W_S = 1$); and the dashed curves are the results for a large asymmetry between $W_S(x)$ and $W_V(x)$ by adopting $\beta_S = 500$ MeV and $\beta_V = 200$ MeV. The data are from EMC(△), SMC(□), E142(◇), and E143(○) experiments [1, 2, 3, 4].

Fig. 4. The quark helicity distributions (a) $x\Delta u_v$ and (b) $x\Delta d_v$ as functions of the Bjorken scaling variable $x$. The thick full, dotted, and dashed
curves are the calculated results for slight asymmetric Wigner rotation, no Wigner rotation, and large asymmetric Wigner rotation respectively corresponding to fig.3. The thin full curves represent limits given by unpolarized quark distributions (i.e., $|\Delta q_v| \leq q_v$). The data (●) are the SMC results from semi-inclusive hadron asymmetries in polarized deep inelastic scattering [12].
