Bag model prediction for the nucleon’s chiral-odd twist-3 distribution $h_L(x, Q^2)$ at high $Q^2$

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Abstract

We study the $Q^2$ evolution of the nucleon’s chiral-odd twist-3 distribution $h_L(x, Q^2)$ starting from the MIT bag model calculation. A simple GLAP equation for $h_L(x, Q^2)$ obtained at large $N_c$ is used for the $Q^2$ evolution. The correction due to the finite value of $N_c$ is $O(1/N_c^2) \sim 10\%$ level. It turns out that the twist-3 contribution to $h_L(x, Q^2)$ is significantly reduced at $Q^2 = 10$ GeV$^2$ in contrast to the $g_2(x, Q^2)$ case. This is due to the fact that the corresponding anomalous dimension for $h_L$ is larger than that for $g_2$ at small $n$ (spin).
The EMC measurement of the nucleon’s $g_1$ structure function [1] inspired lots of theoretical activities on the nucleon’s spin-structure functions in general as well as more precision measurements of $g_1$ [2]. These structure functions provide us with a rich source of information about the spin distributions of quarks and gluons inside the nucleon. Jaffe and Ji [3] discussed general features of the quark distributions of the nucleon and relevant places where they can be measured. The nucleon has three independent twist-2 quark distributions, $f_1(x, Q^2)$ (spin-average), $g_1(x, Q^2)$ (helicity asymmetry), $h_1(x, Q^2)$ (helicity flip), and three independent twist-3 quark distributions $e(x, Q^2), g_2(x, Q^2), h_L(x, Q^2)$. Twist-2 distributions have a simple parton model interpretation and contribute to various hard processes in the leading order with respect to $1/Q^2$. ($Q$ is the hard momentum of the external hard probe.) On the other hand, the twist-3 distributions represent complicated quark-gluon correlations in the nucleon, and is generally difficult to be measured, since they are often hidden behind the leading twist-2 contributions. However, $g_2$ and $h_L$ can be measured in the absence of the leading twist-2 contributions through the proper asymmetries in the polarized deep inelastic scattering and the polarized Drell-Yan process, respectively [4, 5]. In this sense, they are interesting higher twist distribution functions. In fact, E143 collaboration [6] presented a first nonzero data for $g_2$, which anticipates a forthcoming significant progress in twist-3 physics.

So far accumulated experimental data on $f_1$ and $g_1$ allowed us to parametrize in the next-to-leading order for $f_1$ [3] and for $g_1$ [4]. But nothing is known about the actual shape of $h_1$, $g_2$ and $h_L$ except some guess by the bag model calculations [3, 8, 11]. (Since there is no practical way of isolating $e$, it will not be considered in this work.) The bag model has been reasonably successful in describing various properties of hadrons [10], and has been applied to calculate the structure functions [8, 11, 12, 13, 14]. Since the bag model is a low energy effective hadron model, its prediction for the structure functions has to be evolved to higher scale to confront experimental data. After the $Q^2$ evolution, it could approximately reproduce the valence parts of $f_1$ and $g_1$. The purpose of this short note is to present the first and a rough estimate of the magnitude of $h_L(x, Q^2)$ at high $Q^2$ staring from the bag model calculation. We are especially interested in the speed of the $Q^2$-evolution of $h_L$ compared with that of $g_2$ and the chiral-odd twist-2 distribution $h_1$. Since it is not our purpose here to construct a more realistic model, we shall not pursue the projection method to restore the translational invariance as was tried in [9, 12, 13, 14]. We refer those attempts to future studies.

We first recall the definition of the quark distributions in our interest [3]:

$$
\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS | \bar{\psi}(0)^{\lambda} \gamma_\mu \gamma_5 \psi(n) | Q | PS \rangle \\
= 2 \left[ g_1(x, Q^2) p_\mu (S \cdot n) + g_T(x, Q^2) S_{\perp \mu} + M^2 g_3(x, Q^2) S \cdot n n_\mu \right],
$$

(1)

$$
\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS | \bar{\psi}(0)^{\lambda} \gamma_\mu \gamma_5 \psi(n) | Q | PS \rangle = 2 \left[ h_1(x, Q^2) (S_{\perp \mu} p_\nu - S_{\perp \nu} p_\mu) / M \\
+ h_L(x, Q^2) M (p_\mu n_\nu - p_\nu n_\mu) (S \cdot n) + h_3(x, Q^2) M (S_{\perp \mu} n_\nu - S_{\perp \nu} n_\mu) \right],
$$

(2)

where $|PS\rangle$ denotes the nucleon (mass $M$) state with the four momentum $P$ and the spin $S$, and the two light-like vectors, $p$ and $n$, are introduced by the relation $P^\mu = p^\mu + \frac{M^2}{\sqrt{2}} n^\mu$, $p \cdot n = 1$, $p^2 = n^2 = 0$. For the nucleon moving in the $z$-direction, $p = \mathcal{P}/\sqrt{2}(1, 0, 0, 1)$ and $n = \frac{1}{\sqrt{2}} \mathcal{P}(1, 0, 0, -1)$. $\mathcal{P} \rightarrow \infty$ corresponds to the infinite momentum frame and $\mathcal{P} = M/\sqrt{2}$.
corresponds to the nucleon’s rest frame. \( S^\mu \) is decomposed as \( S^\mu = (S_n)p^\mu + (S_p)n^\mu + S^\mu_L \). In [8] and [9], lightcone gauge, \( n \cdot A \sim A^+ = 0 \), was employed. The above distribution functions \( g_1,T \) \( (g_T = g_1 + g_2) \) and \( h_{1,L} \) etc are defined for each quark flavor \( \psi = \psi^a \ (a = u,d,s,...) \) and have support \(-1 < x < 1\). The replacement \( \psi^a \rightarrow C\psi^aT \), \( \bar{\psi}^a \rightarrow -\psi^aC^{-1} \) defines the anti-quark distributions \( \bar{g}_1^T(x) \) etc for each quark distribution \( g_1^T(x) \) etc. They are related as \( g_1^{1,T}(-x) = g_1^{1,T}(x) \), \( h_{1,L}(-x) = -h_{1,L}(x) \). For the polarized deep inelastic scattering, physically measurable structure functions are the combination \( \sum_a e_a^2(g_1^{1,T}(x) + g_1^{2,T}(x)) \) with the Bjorken \( x \) \((0 < x < 1)\) and the electric charge of a (anti-)quark flavor \( a, e_a \). Here and below, we often suppress the explicit \( Q^2 \) dependence of the distributions.

The \( Q^2 \) dependence of these structure functions is calculable in perturbative QCD. The twist-2 distributions, \( g_1 \) and \( h_1 \), obey simple GLAP equations [14]. On the other hand, the \( Q^2 \) dependence of the twist-3 distributions, \( g_2 \) and \( h_L \), is quite sophisticated because the number of quark-gluon-quark operators increases with the moments (or spin). The calculation of the one-loop anomalous dimension matrix for all the twist-3 distributions has been completed [17, 18, 19, 20, 21], and an analogue of GLAP equation relevant to describe \( Q^2 \) evolution of the whole \( x \) dependent distributions has also been derived in [18, 21]. These equations for the twist-3 distributions are the evolution equation for the corresponding parent distributions and is not convenient for practical applications. However, there is a very useful news for physicists working on higher twist effects. It has been proved that at large \( N_c \), the \( Q^2 \) evolution of all the twist-3 distributions is described by simple GLAP equations with slightly different forms for the anomalous dimensions from the twist-2 distributions [22, 23, 24].

The \( Q^2 \) evolution (for \( g_2 \), only for nonsinglet piece) is given by

\[
\mathcal{M}_n \left[ \tilde{g}_2(Q^2) \right] = L^2_{n/b_0} \mathcal{M}_n \left[ \tilde{g}_2(\mu^2) \right],
\]

\[
\mathcal{M}_n \left[ h_L(Q^2) \right] = L^2_{n/b_0} \mathcal{M}_n \left[ h_L(\mu^2) \right],
\]

\[
\mathcal{M}_n \left[ e(Q^2) \right] = L^2_{n/b_0} \mathcal{M}_n \left[ e(\mu^2) \right],
\]

where \( \mathcal{M}_n[g(Q^2)] \equiv \int_1^x dx x^n g(x,Q^2) \), \( L \equiv \alpha_s(Q^2)/\alpha_s(\mu^2) \), \( b_0 = \frac{11}{3}N_c - \frac{2}{3}N_f \). \( \tilde{g}_2 \) and \( \tilde{h}_L \) denote the twist-3 parts of \( g_2 \) and \( h_L \), respectively. The corresponding anomalous dimensions in (3)- (5) are given by

\[
\gamma_n^g = 2N_c \left( S_n - \frac{1}{4} + \frac{1}{2(n+1)} \right),
\]

\[
\gamma_n^h = 2N_c \left( S_n - \frac{1}{4} + \frac{3}{2(n+1)} \right),
\]

\[
\gamma_n^e = 2N_c \left( S_n - \frac{1}{4} - \frac{1}{2(n+1)} \right),
\]

with \( S_n = \sum_{j=1}^n \frac{1}{j} \). Furthermore, these anomalous dimensions are the lowest eigenvalues of the anomalous dimension matrices at large \( N_c \). Since these relations are obtained by a mere replacement \( C_F = (N_c^2 - 1)/2N_c \rightarrow N_c/2 \) in the complete one-loop anomalous dimension

\[\footnote{In a recent work[24], it has also been shown that the same simplification at large \( N_c \) occurs for the \( Q^2 \) dependence of all the twist-3 fragmentation functions.} \]
matrices at finite $N_c$, the correction due to the finite value of $N_c$ is $O(1/N_c^2) \sim 10\%$ level, which is sufficient for practical application. The essential ingredient in (3)-(8) is that a knowledge on $g_2(x)$, $h_L(x)$ and $e(x)$ at one scale is sufficient to predict them at an arbitrary scale, which is not the case at finite $N_c$. This fact provides us with a useful framework to confront experimental data at various $Q^2$ of the twist-3 distribution. In fact (8) and (9) were used to predict the shape of $g_2$ at high $Q^2$ starting from the bag model calculation (4). A more favorable feature of $h_L$ compared with $g_2$ is that $h_L$ does not mix with gluon distributions owing to its chiral-odd nature. Therefore $Q^2$ evolution for $h_L$ and $e$ is given by (4), (5), (7) and (8) even for the flavor singlet piece and thus we can get more reliable and accurate form in the small $x$ region compared to $g_2$. This work is devoted to the study of $Q^2$ evolution of $h_L$ with (4) and (7).

In the rest frame of the nucleon, one can conveniently calculate the above distributions using the MIT bag model. The result for $h_1$ and $h_L$ with one quark flavor in the nucleon is given as

$$
\begin{align*}
    h_1(x) &= \frac{\omega MR}{2\pi(\omega-1)j_0^2(\omega)} \int_{|y_{min}|}^{\infty} dy y \left[ t_0(\omega, y)^2 + 2t_0(\omega, y)t_1(\omega, y)\frac{y_{min}}{y} + t_1(\omega, y)^2\left(\frac{y_{min}}{y}\right)^2 \right], \\
    h_L(x) &= \frac{\omega MR}{2\pi(\omega-1)j_0^2(\omega)} \int_{|y_{min}|}^{\infty} dy y \left[ t_0(\omega, y)^2 - t_1(\omega, y)^2\left(2\left(\frac{y_{min}}{y}\right)^2 - 1\right) \right].
\end{align*}
$$

(9) (10)

Here $t_l$ is given by

$$
t_l(\omega, y) = \int_0^1 dz z^2 j_l(\omega z) j_l(y z),
$$

(11)

where $j_l$ is the $l$-th order spherical Bessel function, and $\omega$ is determined by the relation $\tan \omega = -\omega/(\omega-1)$. For the lowest energy mode, $\omega = 2.04$. $y_{min}$ is defined as $y_{min} = MRx - \omega$ with the bag radius $R$ determined by the relation $MR = 4\omega$. $h_L$ is decomposed into the twist-2 piece which can be expressed in terms of $h_1$ and a purely twist-3 piece $\tilde{h}_L$ as

$$
h_L(x) = \begin{cases} 
    2x \int_x^1 dy \frac{h_1(y)}{y^2} + \tilde{h}_L(x), & 0 < x < 1 \\
    -2x \int_{-1}^x dy \frac{h_1(y)}{y^2} + \tilde{h}_L(x), & -1 < x < 0
\end{cases}
$$

(12)

The bag model prediction above has to be regarded as a distribution at some low energy scale $Q^2 = \mu_{bag}^2 \leq 1$ GeV$^2$. For $h_1$, we regard (3) as a valence distribution at this low energy scale.

In order to evolve the bag model prediction for $h_L$ from $\mu_{bag}^2$ to $Q^2$ according to (4), we used a method in (23). For the moment, we symbolically represent $h_{1,L}(x)$ by $h(x)$. If one defines $h_{\pm}(x) = h(x)\pm h(-x) = h(x)\mp h(x)$, the even (odd) moments of $h_{\pm}(x)$ ($h_{-}(x)$) on the interval $[0, 1]$ agree with $\mathcal{M}_n[h]$, whose $Q^2$ evolution is given by (4) and (7) and its analogue. We assume $Q^2$ evolution of all the moments of $h_{\pm}(x)$ and $h_{-}(x)$ on $[0, 1]$ is described by the same anomalous dimensions as was often assumed to describe $Q^2$ evolution of $f_1(x, Q^2)$
and $g_1(x, Q^2)$, and construct $h(x, Q^2)$ on $[-1, 1]$. This is equivalent to assume that the $Q^2$ dependence of the moments of $h(x, Q^2)$ on $[0, 1]$ and $[-1, 0]$ are separately governed by the same anomalous dimension in (7), which is a sufficient condition to satisfy (4). To describe the method in [25], we introduce Bernstein polynomial defined by

$$b^{(N,k)}(x) = (N + 1){n \choose k}x^k(1-x)^{N-k} = (N + 1)! \sum_{l=0}^{N-k} \frac{(-1)^l x^{k+l}}{l!(N-k-l)!}.$$  \hspace{1cm} (13)

and note that it satisfies the relation

$$\lim_{N,k \to \infty} l/N \to x b^{(N,k)}(y) = \delta(x-y)$$ \hspace{1cm} (14)

for $0 < x, y < 1$. Using (14), (4) and (7), we get

$$\tilde{h}_L(x, Q^2) = \lim_{N,k \to \infty} \left( \frac{N + 1}{k!} \sum_{l=0}^{N-k} \frac{(-1)^l}{l!(N-k-l)!} \int_0^1 dy y^{k+l} \tilde{h}_L(y, Q^2) \right)$$

$$= \lim_{N,k \to \infty} \left( \frac{N + 1}{k!} \sum_{l=0}^{N-k} \frac{(-1)^l}{l!(N-k-l)!} L^\gamma_h y^{k+l} \tilde{h}_L(y, \mu^2) \right),$$ \hspace{1cm} (15)

Since the summation over $l$ in (15) oscillates due to the factor $(-1)^l$, the direct use of (15) is not convenient. To avoid this difficulty we shall utilize the following procedure. Expand $L^\gamma_h$ as

$$L^\gamma_h = a(L) \sum_{i=0} C_i(L) (n+p)^{i+\rho(L)},$$ \hspace{1cm} (16)

where $a(L)$, $C_i(L)$ and $p$ are the constants determined below. Then (15) is rewritten as

$$h(x, Q^2) = \int_x^1 \frac{dy}{y} b(x, y; Q, \mu) h(y, \mu),$$

$$b(x, y; Q, \mu) \equiv a(L) \left( \frac{x}{y} \right)^{p-1} \sum_{i=0} \left( \ln \frac{y}{x} \right)^{i+\rho-1} \frac{C_i}{\Gamma(i+\rho)},$$ \hspace{1cm} (17)

where we have used the relation

$$\lim_{N,k \to \infty} \frac{N + 1}{k!} \sum_{l=0}^{N-k} \frac{(-1)^l}{l!(N-k-l)!} y^{k+l} \frac{1}{(k+l+p)^{i+\rho}} = \theta(y-x) \frac{1}{\Gamma(i+\rho+y)} \left( \frac{x}{y} \right)^{p-1} \left( \ln \frac{y}{x} \right)^{i+\rho-1}. \hspace{1cm} (18)$$

The expansion (16) can be obtained by applying the following asymptotic expansion to $\gamma_h$ in (7):

$$S_{n+1} \sim \gamma_E + \ln(n + 1) + \frac{1}{2(n + 1)} - \sum_{k=1}^{\infty} \frac{B_{2k}}{2k(n + 1)^{2k}}$$ \hspace{1cm} (19)
where $\gamma_E = 0.577...$ is the Euler constant and $B_{2k}$'s are the Bernoulli numbers. This procedure gives $p = 1$ and the coefficients $C_i$ in (16). (See [23, 3] for the details.) We have used first four terms (i.e. up to $B_8$) in the expansion (19), which gives enough precision.

Next we need to determine the bag scale $\mu_{bag}$. Phenomenological values for $\mu_{bag}^2$ adopted in the previous studies scatters below 1 GeV$^2$: Jaffe and Ross [20] extracted $\mu_{bag}^2 = 0.75$ GeV$^2$ from the 5-th moment of a $F_3$ data. Schreiber et al. [13] took $\mu_{bag}^2 = 0.25$ GeV$^2$ to reproduce approximate shape of $F_2$ at $Q^2 = 10$ GeV$^2$. More recently, Stratmann determined $\mu_{bag}^2 = 0.081$ GeV$^2$ by comparing the second moment (momentum sum rule) of the bag model prediction with that of the valence distribution determined by Glück et al. [3].

Our purpose here is to see how $h_L$ evolves compared with other distributions such as $h_1$ and $g_2$, and therefore we shall show the results for two values of $\mu_{bag}^2$, $\mu_{bag}^2 = 0.081, 0.25$ GeV$^2$, for future references. For other parameters, we set $N_f = 3$, $\Lambda_{QCD} = 0.232$ GeV in $\alpha_s(Q^2)$.

Figure 1 (a) and (b) show the results for $xh_1(x,Q^2)$ and $xg_1(x,Q^2)$ at $Q^2 = 10$ GeV$^2$ with two values of $\mu_{bag}^2$ together with the bag calculations. For the $Q^2$ evolution, we have used the anomalous dimension for $h_1$ calculated in [27, 19]. $g_1(x,Q^2)$ at $Q^2 = 10$ GeV$^2$ is strongly peaked in the small $x$ region, since the anomalous dimension for $\mathcal{M}_0[g_1]$ is zero while it is $4/3$ for $\mathcal{M}_0[h_1]$. (If one plots $h_1$ and $g_1$ instead of $xh_1$ and $xg_1$, this feature is more conspicuous.) Figure 2 shows the bag calculation for $h_L$ decomposed into the twist-2 and -3 contributions [4] (a)) and $h_L$ evolved to $Q^2 = 10$ GeV$^2$ with $\mu_{bag}^2 = 0.081$ GeV$^2$ ((b)) and $\mu_{bag}^2 = 0.25$ GeV$^2$ ((c)). In Fig. 3, we plot only the twist-3 piece of $h_L$, $\tilde{h}_L$, taken from Fig. 2 to see how it evolves with $Q^2$. These graphs show clearly that at higher $Q^2$ the contribution from $\tilde{h}_L(x,Q^2)$ is significantly reduced and $h_L(x,Q^2)$ is dominated by the twist-2 contribution. Although our calculation starts from the bag model prediction, this tendency can be taken as model independent. Comparison of Fig. 3 and Fig. 1 shows that $\tilde{h}_L$ evolves faster than $h_1$ as is expected from the magnitudes of the anomalous dimensions [13]. For comparison we have also shown $g_2(x,Q^2)$ in Fig. 4. Since this distribution is accessible in the polarized DIS, we plotted the combination $g_2(x,Q^2) + \tilde{g}_2(x,Q^2) = g_2(x,Q^2) + g_2(-x,Q^2)$ for one quark-flavor with unit charge. At the bag scale, twist-3 contribution $\tilde{g}_2$ is comparable to the twist-2 contributin as in the case of $h_L$. This feature more or less survives even at $Q^2 = 10$ GeV$^2$ in contrast to the $h_L$ case. This is because $\gamma_n^h > \gamma_n^g$ especially at small $n$ and hence $Q^2$ evolution of $\tilde{h}_L$ in the small $x$ region is faster than that of $\tilde{g}_2$. As was stated before, flavor-singlet part of $g_2$ mixes with the gluon distribution and $Q^2$ evolution of singlet $\tilde{g}_2$ is not given by (3). Singlet $\tilde{g}_2$ is probably more enhanced at small $x$ region. If the bag model gives a good description even for the twist-3 distribution $h_L$, our present study indicates that it will be extremely difficult to extract $\tilde{h}_L(x,Q^2)$ at high $Q^2$. On the other hand, if future experiments show $\tilde{h}_L(x,Q^2)$ is still sizable at high $Q^2$, it means that the naive bag model calculation is not suitable to describe quark-gluon correlation represented by $h_L$ in the nucleon. In any case, it is very interesting to confirm these general features in the future collider experiments.

\footnote{Comparison with other parton distributions in [3] gives almost the same numbers for $\mu_{bag}$.}
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Figure captions

**Fig. 1** (a) Bag model calculation for $xh_1(x)$ (dash-dot line) and $h_1(x, Q^2 = 10 \text{ GeV}^2)$ with $\mu_{\text{bag}}^2=0.081 \text{ GeV}^2$ (solid line) and 0.25 $\text{ GeV}^2$ (dashed line). (b) The same as (a) but for for $xg_1(x, Q^2)$.

**Fig. 2** (a) Bag model calculation for $h_L(x)$ (solid line) decomposed into the twist-2 (dashed line) and the twist-3 (dash-dot line) contributions. (b) $h_L(x, Q^2)$ at $Q^2 = 10 \text{ GeV}^2$ with $\mu_{\text{bag}}^2 = 0.081 \text{ GeV}^2$ decomposed into the twist-2 and twist-3 contributions. (c) The same as (b) but with $\mu_{\text{bag}}^2 = 0.25 \text{ GeV}^2$.

**Fig. 3** Twist-3 contribution to $h_L(x, Q^2)$ at the bag scale (dash-dot line) and $Q^2 = 10 \text{ GeV}^2$ with $\mu_{\text{bag}}^2=0.081 \text{ GeV}^2$ (solid line) and 0.25 $\text{ GeV}^2$ (dashed line).

**Fig. 4** (a) Bag model calculation for $g_2(x)$ decomposed into the twist-2 ($g_2^{WW}(x)$) and the twist-3 ($g_2(x)$) contributions. (b) $g_2(x, Q^2)$ at $Q^2 = 10 \text{ GeV}^2$ with $\mu_{\text{bag}}^2 = 0.081 \text{ GeV}^2$. (c) The same as (b) but with $\mu_{\text{bag}}^2 = 0.25 \text{ GeV}^2$. 
Fig. 1(a)
Bag model

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \mu^2_{\text{bag}} = 0.081 \text{ GeV}^2 \]

\[ \mu^2_{\text{bag}} = 0.25 \text{ GeV}^2 \]

Fig. 1(b)
Fig. 2(a)
Fig. 2(b)

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \mu^2_{\text{bag}} = 0.081 \text{ GeV}^2 \]
$Q^2 = 10 \text{ GeV}^2$

$\mu^2_{\text{bag}} = 0.25 \text{ GeV}^2$
$\mu^2_{\text{bag}} = 0.081 \text{ GeV}^2$

$\mu^2_{\text{bag}} = 0.25 \text{ GeV}^2$

$Q^2 = 10 \text{ GeV}^2$

Fig. 3
Fig. 4(a)
$g_2(x, Q^2)$

Fig. 4(b)

$Q^2 = 10 \text{ GeV}^2$

$\mu^2_{\text{bag}} = 0.081 \text{ GeV}^2$
\( Q^2 = 10 \text{ GeV}^2 \)
\( \mu^2_{\text{bag}} = 0.25 \text{ GeV}^2 \)