COMPARATIVE ANALYSIS OF TRANSVERSITIES AND LONGITUDINALLY POLARIZED DISTRIBUTIONS OF THE NUCLEON

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Abstract

We carry out a comparative analysis of the transversities and the longitudinally polarized parton distribution functions in light of the first empirical extraction of the transversity distributions recently done by Anselmino et al. It is shown that the precise determination of the isoscalar tensor charge, which is defined as the 1st moment of the isoscalar combination of the transversity distributions, is of fundamental importance for clarifying the internal spin structure function of the nucleon.

As is well known, the transversity is one of the three fundamental parton distribution functions (PDFs) with the lowest twist 2. Different from the other two, i.e. more familiar unpolarized PDF and the longitudinally polarized PDF, its chiral-odd nature prevents us from extracting it directly through the standard inclusive deep-inelastic-scattering measurements [1],[2]. For this reason, we have had little empirical information on it until recently. Very recently, however, Anselmino et al. succeeded to get a first empirical information on the transversities [3] from the combined global analysis of the azimuthal asymmetries in semi-inclusive DIS scatterings measured by HERMES and COMPASS groups [4],[5], and those in $e^+e^- \rightarrow h_1 h_2 X$ processes by the Belle Collaboration [6]. Their main observation for the transversities can be summarized as follows. First, the $u$-quark transversity is positive and $d$-quark one is negative with the magnitude of $\Delta T_u(x)$ being much larger than that of $\Delta T_d(x)$. Second, both of $\Delta T_u(x)$ and $\Delta T_d(x)$ are significantly smaller than the Soffer bound [7]. The 2nd observation is only natural, since the magnitudes of unpolarized PDFs are generally much larger than the polarized PDFs. In our opinion, what is more interesting from the physical viewpoint is the comparison of the transversities with the longitudinally polarized PDFs. This comparative analysis of the two fundamental PDFs is the main purpose of my present talk [8].

Before going into the comparative analysis of the transversities and the longitudinally polarized PDFs, it would be useful to give an overview of new measurements of the longitudinally polarized PDFs, especially in the flavor singlet channel related to the nucleon spin problem. Recently, the COMPASS and HERMES groups carried out high-statistics measurements of the longitudinal spin structure function of the deuteron, thereby having succeeded to significantly reduce the error bars of $\Delta \Sigma$, the net quark spin contribution to the nucleon spin [9]-[11].

As pointed out in [12], these new results for the deuteron spin structure function is remarkably close to our theoretical predictions given some years ago based on the chiral quark soliton model (CQSM) [12],[14]. (See also [15]-[18].) Fig[1] show the comparison
Figure 1: The predictions of the $SU(2)$ and $SU(3)$ CQSM in comparison with the new COMPASS data for $xg_1^d(x)$ (filled circles) and their NLO QCD fits (long-dashed curve). The old SMC data \cite{19} are also shown by open squares.

Figure 2: The predictions of the $SU(2)$ and $SU(3)$ CQSM in comparison with the new COMPASS data for $g_1^N(x)$ (filled circles) and their NLO QCD fits (long-dashed curve).

between our predictions for $xg_1^d(x, Q^2)$ given several years ago and the new COMPASS data \cite{11} (the filled circles) together with the old SMC data \cite{19} (the open squares). The solid and dashed curves respectively stand for the predictions of the flavor $SU(3)$ and $SU(2)$ CQSM evolved to the energy scale $Q^2 = 3 \text{GeV}^2$, which is the average energy scale of the new COMPASS measurement. The long-dashed curve shown for reference is the next-to-leading order QCD fit by the COMPASS group \cite{10}. As one can see, the new COMPASS data show a considerable deviation from the old SMC data in the small $x$ region. One finds that the predictions of the CQSM are consistent with the new COMPASS data especially in the small $x$ region. This tendency can more clearly be seen in comparison of $g_1^0(x) \equiv g_1^d(x)/(1 - \frac{3}{2}\omega_D)$ illustrated in Fig.2. The filled circles here represent the new COMPASS data for $g_1^N(x)$, while the long-dashed curve is the result of the next-to-leading order QCD fit by the COMPASS group \cite{10}. The predictions of the $SU(3)$ and $SU(2)$ CQSM are represented by the solid and dashed curves, respectively. For the quantity $g_1^N(x)$, the experimental uncertainties are still fairly large in the small $x$ region. Still, one can say that the predictions of the CQSM is qualitatively consistent with the new COMPASS data as well as their QCD fit.

The COMPASS group also extracted the matrix element of the flavor-singlet axial charge $a_0$ \cite{10}, which can be identified with the net longitudinal quark polarization $\Delta \Sigma$ in the $\overline{\text{MS}}$ factorization scheme. Taking the value of $a_0$ from the hyperon beta decay, under the assumption of $SU(3)$ flavor symmetry, they extracted from the QCD fit of the new COMPASS data for $g_1^d(x)$ the value of $\Delta \Sigma$ as

$$
\Delta \Sigma(Q^2 = 3 \text{GeV}^2)_{\text{COMPASS}} = 0.35 \pm 0.03 \text{ (stat.)} \pm 0.05 \text{ (syst.)}.
$$

On the other hand, the same quantity derived from the fits to all $g_1$ data is a little smaller

$$
\Delta \Sigma(Q^2 = 3 \text{GeV}^2)_{\text{COMPASS}} = 0.30 \pm 0.01 \text{ (stat.)} \pm 0.02 \text{ (evol.)}.
$$
A similar analysis was also reported by the HERMES group [11]. Their result is

\[ \Delta \Sigma(Q^2 = 5 \text{ GeV}^2)_{\text{HERMES}} = 0.330 \pm 0.011 \,(\text{theor.}) \pm 0.025 \,(\text{exp.}) \pm 0.028 \,(\text{evol.}). \tag{3} \]

The results of the two groups for \( \Delta \Sigma \) are mutually consistent and seems to be larger than the previously known central values [19]. We now compare these new results with the prediction of the CQSM given in our previous papers [13], [14]. Shown in Fig. 3 are the prediction of the CQSM for \( \Delta \Sigma \) and \( \Delta g \) as functions of the energy scale \( Q^2 \). They are obtained by solving the standard DGLAP equation at the NLO with the prediction of the model as the initial condition given at the scale \( Q^2_{\text{ini}} = 0.30 \text{ GeV}^2 \simeq (600 \text{ MeV})^2 \). Since the CQSM is an effective quark model, which contains no gluon degrees of freedom, \( \Delta g \) is simply assumed to be zero at the initial scale. One sees that the new COMPASS and the HERMES results for \( \Delta \Sigma \) are surprisingly close to the prediction of the CQSM. Also interesting is the longitudinal gluon polarization \( \Delta g \). In spite that we have assumed that \( \Delta g \) is zero at the starting energy, it grows rapidly with increasing \( Q^2 \). As pointed out in [20], the growth of the gluon polarization with \( Q^2 \) can be traced back to the positive sign of the anomalous dimension \( \gamma_{gg}^{(0)} \). The positivity of this quantity dictates that the polarized quark is preferred to radiate a gluon with helicity parallel to the quark polarization. Since the net quark spin component in the proton is positive, it follows that \( \Delta g > 0 \) at least for the gluon perturbatively emitted from quarks. The growth rate of \( \Delta g \) is so fast especially in the relatively small \( Q^2 \) region that its magnitude reaches around \((0.3 - 0.4)\) already at \( Q^2 = 3 \text{ GeV}^2 \), which may be compared with the estimate given by the COMPASS group:

\[ \Delta g(Q^2 = 3 \text{ GeV}^2)_{\text{COMPASS}} \simeq (0.2 - 0.3). \tag{4} \]

Now that we have convinced that the CQSM reproduces very well the longitudinally polarized PDFs of the nucleon and the deuteron, we return to the main topic of this talk, i.e. the difference of the longitudinally polarized PDFs and the transversities. First, I recall that the most important quantities characterizing these PDFs are their 1st moments, known as the axial and tensor charges. Next, I emphasize that the understanding of isospin dependencies is crucially important to disentangle the nonperturbative chiral dynamics of QCD hidden in the PDFs. Neglecting the strange quark degrees of freedom, for simplicity, there exist two independent combinations: the isoscalar and isovector combinations for both of the axial and tensor charges.
Let us first recall some basic facts about the axial and tensor charges. The difference of the axial and tensor charges is of purely relativistic nature [1]. In fact, in the naive quark model or the nonrelativistic quark model, there is no difference between the axial and tensor charges, that is, the isovector axial and tensor charges are both $\frac{5}{3}$, while the isoscalar axial and tensor charges are both unity:

$$g_A^{(I=1)} = g_T^{(I=1)} = \frac{5}{3}, \quad g_A^{(I=0)} = g_T^{(I=0)} = 1. \quad (5)$$

On the other hand, in the familiar MIT bag model, which is nothing but the valence quark model with the relativistic kinematics, an important difference appear between the axial and tensor charges due to the presence of the lower component of the ground state wave function $g(r)$ as

$$g_A^{(I=0)} = 1 \cdot \int \left( f^2 - \frac{1}{3} g^2 \right) r^2 dr, \quad g_A^{(I=1)} = \frac{5}{3} \cdot \int \left( f^2 - \frac{1}{3} g^2 \right) r^2 dr, \quad (6)$$

$$g_T^{(I=0)} = 1 \cdot \int \left( f^2 + \frac{1}{3} g^2 \right) r^2 dr, \quad g_T^{(I=1)} = \frac{5}{3} \cdot \int \left( f^2 + \frac{1}{3} g^2 \right) r^2 dr. \quad (7)$$

Nevertheless, an important observation is that the ratio of the isoscalar to isovector charge is just common for the axial and tensor charges, i.e. they are three fifth in both of the NQM and the MIT bag model:

$$\frac{g_A^{(I=0)}}{g_A^{(I=1)}} = \frac{g_T^{(I=0)}}{g_T^{(I=1)}} = \frac{3}{5}. \quad (8)$$

Most probably, this feature is related to a common shortcoming of these models, that is, the lack of the spontaneous chiral symmetry breaking mechanism. One can convince it by comparing the predictions of the MIT bag model with those of the CQSM, which is an effective model of QCD taking account of the effect of spontaneous chiral symmetry breaking in a maximal way.

|           | MIT bag | CQSM | Experiment          |
|-----------|---------|------|---------------------|
| $g_A^{(I=1)}$ | 1.06    | 1.31 | 1.267 (scale independent) |
| $g_A^{(I=0)}$ | 0.64    | 0.35 | 0.330 ± 0.040 ($Q^2 = 5\text{GeV}^2$) |
| $g_T^{(I=1)}$ | 1.34    | 1.21 |                     |
| $g_T^{(I=0)}$ | 0.88    | 0.68 |                     |
| $g_A^{(I=0)} / g_A^{(I=1)}$ | 0.60    | 0.27 | $\sim 0.26$ ($Q^2 = 5\text{GeV}^2$) |
| $g_T^{(I=0)} / g_T^{(I=1)}$ | 0.60    | 0.56 |                     |

Table 1: The predictions of the MIT bag model and of CQSM for the axial and tensor charges in comparison with the empirical information.

As mentioned, in the MIT bag model, the ratio of the isoscalar and isovector axial charges and also the ratio of isoscalar and isovector tensor charges are both exactly 0.6. On the other hand, the CQSM predicts that the ratio of the axial charges is much smaller
than that of the tensor charges. This comes from the fact that the CQSM predicts very small isoscalar axial charge just consistent with the EMC observation, while its prediction for the isoscalar tensor charge is not extremely different from the prediction of other low energy effective models including the MIT bag model.

In any case, the predictions of the CQSM for the axial and tensor charges can roughly be summarized as follows. The isovector tensor and axial charges have the same order of magnitudes, while the isoscalar tensor charge is not so small as the isoscalar axial charge. From this analysis, we immediately expect the following qualitative features for the transversity and the longitudinally polarized PDFs. The isovector transversity distribution and the isovector longitudinally polarized distribution would have the same order of magnitude, while the isoscalar $\Delta_T q(x)$ is much larger than the isoscalar $\Delta q(x)$, i.e.

$$\Delta q^{(I=0)}(x) \ll \Delta_T q^{(I=0)}(x), \quad \Delta q^{(I=1)}(x) \simeq \Delta_T q^{(I=1)}(x). \quad (9)$$

In other words, we would expect the magnitude of $d$-quark transversity is much smaller than that of $d$-quark longitudinally polarized PDF:

$$|\Delta_T d(x)| \ll |\Delta d(x)|. \quad (10)$$

To make the argument more quantitative, we compare in Fig.4 the CQSM predictions for the transversities and the longitudinally polarized PDFs. Here, the model predictions are evolved to the energy scale of $Q^2 = 2.4\;\text{GeV}^2$, for later convenience. One can confirm that the magnitudes of the $u$-quark transversities and the $u$-quark longitudinally polarized PDF are roughly the same, whereas the magnitude of $d$-quark transversity is roughly a factor of two smaller than that of the $d$-quark longitudinally polarized PDF.

Now, I compare in Fig.5 the CQSM predictions for the transversities with the recently obtained global fit by Anselmino et al. [3]. As one sees, the uncertainties of the global fit are still quite large. Still, a remarkable feature of the transversity distributions seems to be already seen in their fit. A common feature of the CQSM prediction and their global fit is that the ratio $\Delta_T d(x)/\Delta d(x)$ is very small. As a general trend, however, the magnitudes of the transversities obtained by their global fit look fairly smaller than the corresponding CQSM predictions. In particular, the CQSM prediction for the $u$-quark transversity appears to lie outside the upper limit of their fit. We shall come back to this point later.

At this point, it would be useful to make some comments on the calculation of transversities by Bochum group based on the same CQSM [21]. A main difference between our calculation [13, 22] and theirs [21] resides in the isovector part of transversities $\Delta_T q^{(I=1)}(x)$. In their calculation, they included only the leading-order contribution to this quantity,
and neglected the subleading \(1/N_c\) correction, while we have included the latter as well. This is because we know that a similar \(1/N_c\) correction (or more concretely, the 1st-order rotational correction) is very important for resolving the famous underestimation problem of some isovector observables, like the isovector axial-charge and/or the isovector magnetic moment of the nucleon, inherent in the hedgehog-type soliton model \[23, 24\]. The neglect of this \(1/N_c\) correction would led to a similar underestimation of the isovector tensor charge, thereby having a fear of being lead to a misleading conclusion on the size of the transversities. We emphasized that, to avoid such a danger, it is very important to analyze the transversities and the longitudinally polarized PDFs simultaneously within the same theoretical framework.

![Figure 5: The predictions of the flavor SU(2) CQSM for the transversities (solid curves) in comparison with the global-fit of [3] (shaded areas).](image1)

![Figure 6: The predictions of the flavor SU(2) CQSM for the transversities (solid curves) in comparison with the LSS2005 fit [25] of the longitudinally polarized u- and d-quark distributions.](image2)

To see the difference with the longitudinally polarized PDFs, we show in Fig.?? the LSS2005 fit for the longitudinally polarized u- and d-quark distributions \[25\]. One can confirm that the CQSM prediction for the u-quark transversity has the same order of magnitude as that of the LSS fit for the u-quark longitudinally polarized PDF, while the CQSM prediction for the d-quark transversity is a factor of two smaller than the LSS fit for the longitudinally polarized PDF \[25\].

As already emphasized, the reason of this difference can be traced back to the fact that the isoscalar tensor charge is not so small as the isoscalar axial charge in the CQSM. Then, the next question is why the CQSM predicts so small isoscalar axial charge. First, I recall that in the standard \(\overline{MS}\) scheme the isoscalar axial charge can be identified with the net quark polarization \(\Delta\Sigma\). Within the framework of the CQSM, we can prove the following nucleon spin sum rule, naturally saturated by the quark fields alone \[26\] :

\[
\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L^Q.
\] (11)

On the other hand, in accordance with the physical nucleon picture of the model as a rotating hedgehog, the CQSM predicts quite large quark OAM, which in turn dictates
that $\Delta \Sigma$ must be small [26]. As a matter of course, in real QCD, the correct nucleon spin sum rule contains the gluon contributions as well:

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L^Q + \Delta g + L^g.$$  \hfill (12)

However, all the recent investigations indicate that the $\Delta g$ is likely to be small at least in the relatively low energy scale. Combining these observation, one must therefore conclude that the sum of $L^Q$ and $L^g$ must be fairly large at low energy scale.

Our next question is then, "Is there any sum rule that constrains the magnitudes of the isoscalar tensor charge? Here, one may remember the nucleon spin sum rule proposed by Bakker, Leader and Trueman some years ago [27], which in fact contains the transversity distributions as

$$\frac{1}{2} = \frac{1}{2} \sum_{a=q,\bar{q}} \int_0^1 \Delta_T q^a(x) + \sum_{a=q,\bar{q},g} (L_{ST})^a,$$  \hfill (13)

where $L_{ST}$ is the component of the orbital angular momentum $L$ along the transverse spin direction $s_T$. Unfortunately, there are several peculiarities in the BLT sum rule. First of all, it is not such a sum rule obtained as the 1st moment of some parton distribution functions. In fact, the r.h.s. of this sum rule does not correspond to a nucleon matrix element of local operator. In particular, the 1st term of this sum rule does not correspond to the isoscalar tensor charge, because here the sum of the quarks and antiquarks, not the difference, appear as

$$\sum_{a=q,\bar{q}} \int_0^1 \Delta_T q^a(x) dx = \int_0^1 \left\{ [\Delta_T u(x) + \Delta_T d(x)] + [\Delta_T \bar{u}(x) + \Delta_T \bar{d}(x)] \right\} \neq g_T^{(I=0)}.$$  \hfill (14)

Nonetheless, our analysis based on the CQSM indicates that antiquark transversities are fairly small. This means that the 1st term of the BLT sum rule may not be extremely different from the tensor charge. Then, if the postulated inequality between the isoscalar axial and tensor charges is in fact confirmed experimentally, it would mean the following inequality, that is the transverse OAM is much smaller than the longitudinal OAM:

$$L^Q_{ST} + L^g_{ST} \ll L^Q + L^g.$$  \hfill (15)

At this point, we come back to the discrepancy between the CQSM predictions and the global fit by Anselmino et al. We can estimate the magnitudes of tensor charges from their central fit, under the assumption that the antiquark contributions to them are negligible, as justified by the CQSM. We then get the following values for the $u$- and $d$-quark tensor charges,

$$\delta u \simeq 0.39, \quad \Delta d \simeq -0.16,$$  \hfill (16)

or for the isoscalar and the isovector tensor charges,

$$g_T^{(I=0)} \simeq 0.23, \quad g_T^{(I=1)} \simeq 0.55,$$  \hfill (17)

at the energy scale $Q^2 \simeq 2.4 \text{GeV}^2$. If they are evolved down to the low energy model scale around 600 MeV, we would obtain the following numbers:

$$\delta u \simeq 0.49, \quad \Delta d \simeq -0.20,$$  \hfill (18)
We recall that all the theoretical estimates in the past, based on the low energy models as well as the lattice QCD, predict the isovector tensor charge between 1.0 and 1.5 \[28\]- \[33\]. At any rate, we emphasize that the transversities obtained by their global fit correspond to fairly small magnitudes of tensor charges as compared with the past theoretical estimates.

To sum up, we have carried out a comparative analysis of the transversities and the longitudinally polarized PDFs in light of the new global fit of transversities and the Collins fragmentation functions carried out by Anselmino et al. Their results, although with large uncertainties, already appears to indicate a remarkable qualitative difference between transversities and longitudinally polarized PDFs such that \[|\Delta_T d(x)/\Delta d(x)| \ll |\Delta_T u(x)/\Delta u(x)|\], which is qualitatively consistent with the predictions of the CQSM.

I have emphasized that the cause of this feature can be traced back to the relation 
\[g_T^{(I=0)} \gg g_A^{(I=0)} = \Delta \Sigma.\]

Further combining with the BLT sum rule, this indicates the inequality, \[L^Q_{ST} + L^g_{ST} \ll L^Q + L^g\], i.e. the transverse OAM may be much smaller than the longitudinal OAM. We are not sure whether this unique observation can be understood as the dynamical effects of Lorentz boost or Melosh transformation. Naturally, the global analysis carried out by Anselmino et al. is just a 1st step for extracting transversities. More complete understanding of the spin dependent fragmentation mechanism is mandatory for getting more definite knowledge of the transversities. Also very desirable is some independent determination of transversities, for example, through double transverse spin asymmetry in Drell-Yan processes. We hope that such near-future experiments will provide us with more stringent constraint on the isovector as well as the isoscalar tensor charges, thereby deepening our knowledge on the internal spin structure function of the nucleon.

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