PROBES OF PARTON TRANSVERSY

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ABSTRACT

An inventory is made of the experiments which can measure the transversely polarized quark distributions and fragmentation functions at leading twist.

1. Introduction

*Transversity or transverse spin* states are the linear superpositions

\[ |\hat{\mathbf{n}}> = \left( |+> + \exp(i\phi)|-> \right) / \sqrt{2} \]

of the helicity states |+> and |->; \( \hat{\mathbf{n}} \) is a unit transverse vector of azimuth \( \phi \). Contrarily to the quark helicity distributions \( \Delta_L q(x) = q^+ (x) - q^- (x) \), the *transversity* distributions

\[ \Delta_T q(x) = q^\hat{\mathbf{n}} (x) - q^- \hat{\mathbf{n}} (x) , \]

(in a nucleon of transversity +\( \hat{\mathbf{n}} \)) have never been measured. The most simple covariant parton model\[1\] shows that \( \Delta_T q(x) \) and \( \Delta_L q(x) \) are not redundant informations on the structure of the nucleon. In fact, for a *scalar* spectator diquark, we have \( \Delta_T q(x) = q^\hat{\mathbf{n}} (x) > 0 \), while \( \Delta_L q(x) \) is negative for large enough intrinsic \( < k_T > \); this should apply, for instance, to the s-quark in a \( \Lambda \). For a 1\( ^+ \) diquark, \( \Delta_T q(x) < 0 \), while \( \Delta_L q(x) \) can take any sign. The same results hold for the spin asymmetries \( \Delta_T f(z) \) and \( \Delta_L f(z) \) of the fragmentation functions.

Roughly speaking, \( \Delta_T q(x) \) is the discontinuity of the forward helicity-flip amplitude of quark-hadron scattering (bottom of Fig. 1a); its measurement in ordinary deep inelastic lepton scattering is impeded by quark helicity conservation at the top of Fig. 1a. By contrast, Drell-Yan lepton pair production with polarized beam and target (Fig. 1b) overcomes this difficulty. In this paper, we shall look for all other possible probes of \( \Delta_T q(x) \) and/or \( \Delta_T f(z) \) at leading twist and to minimal order in \( \alpha \) and/or \( \alpha_s \).

2. Reactions with two initial transversely polarized particles\[1,4,6,7,9\]

Let us draw unitarity diagrams of reactions sensitive to quark transversity. We have learned from the example of Fig. 1a. that the line of a transversely polarized quark should not come back to its parent hadron. Thus the reaction must involve at least *two transversely polarized hadrons* (\( A \) and \( B \) in Fig. 2). In this section, we assume that these hadrons are incoming ones. We limit ourself to \( 2 \rightarrow 2 \) subprocesses. The differential cross section takes the general form
Figure 1. Unitarity diagrams for transverse polarization effects a) in deep inelastic lepton scattering (forbidden) ; b) in Drell-Yan lepton pair production (allowed). + or − are helicity signs (except in $\mu^+$ and $\mu^-$). Grey ellipses represent parton distribution functions.

$$d\sigma(\uparrow A + \uparrow B \rightarrow c + d + X) = dx_a \, dx_b \, d\hat{\sigma}(a + b \rightarrow c + d)_{\text{unpol.}} \times \left[ a(x_a) \, b(x_b) - P_A \, P_B \, \Delta T a(x_a) \, \Delta T b(x_b) \, \hat{A}_{NN}(\hat{\theta}) \, \cos(2\phi - \phi_A - \phi_B) \right],$$

where $\vec{P}_A$ and $\vec{P}_B$ are the transverse polarisation vectors of $A$ and $B$, $\phi_A$ and $\phi_B$ their azimuthes and $\hat{A}_{NN}$ is the spin correlation parameter of the subprocess for spin component normal to the scattering plane.

Figure 2. General unitarity diagram for transverse spin asymmetry at leading twist. Grey ellipses : parton distribution- or quark fragmentation functions. Grey circles : subprocess amplitudes. Black triangles indicate the helicity flows ; for helicity $+\frac{1}{2}$ (resp. $-\frac{1}{2}$), they have same (resp. opposite) orientation as particle propagation (the latter is not displayed so that this figure can be used for crossed reactions). In all cases, total helicity flow in the $t$-channel is $+1$.

There are only three different possible routes for the lines of the polarized quarks, shown in Fig. 3. Fig. 3a applies to scattering of identical quarks ; it results from the antisymmetrization principle. The spin asymmetry should
be best seen in $\uparrow p + \uparrow p \rightarrow \pi^+ +$ opposite side $\pi^+$ at large $x_T$. Unfortunately, $\hat{A}_{NN}(90^\circ)$ is only $-1/11$.

Fig. 3b describes any $q\bar{q}$ annihilation process: $c + d$ can be one of the following combinations: $l^+ l^-$ (Fig. 1b), $\gamma \gamma$, $\gamma G$, $GG$, $q' q'$, $Q \bar{Q}$. ($\gamma =$ ”direct” photon, $G =$ gluon jet, $q' =$ light quark jet, $Q =$ heavy quark). All these processes have $\hat{A}_{NN}(90^\circ) \sim 1$ but need a polarized antiproton beam to obtain a substantial asymmetry, because the sea transversity is probably small.

Fig. 3c represents the interference between the $\hat{s}$-channel and $\hat{t}$-channel poles in $q\bar{q}$ scattering. Note that in all three cases of Fig. 3, parton $a$ and $b$ have identical or opposite flavors.

3. Reactions with one initial and one final transversely polarized particles

The subprocess $\uparrow a + \uparrow b \rightarrow c + d$ can be crossed into $\uparrow a + \bar{c} \rightarrow \uparrow \bar{b} + d$ and the parton distribution $b(x_b)$ into the fragmentation function $f_{b \rightarrow \bar{B}}(z)$. Renaming $\bar{B}$, $\bar{b}$ and $\bar{c}$ by $B$, $b$ and $c$, we can use Figs. 2 and 3 again; $c$ is now an initial pointlike particle and $B$ a final hadron which has transverse polarization

$$\vec{P}_T(B) = R_{AB} \vec{P}_T(A) \times \frac{\Delta_T a(x)}{a(x)} \times \frac{\Delta_T f_{b \rightarrow \bar{B}}(z)}{f_{b \rightarrow B}(z)} \times \hat{D}_{NN}(\hat{\theta}) ;$$

$R_{AB}$ is the rotation which brings $\vec{p}_A$ along $\vec{p}_B$ in the scattering plane and $\hat{D}_{NN}(\hat{\theta})$ the depolarization parameter of the subprocess. We need to polarize only the target but we have to analyse the spin of a final particle.

$(c, d) = (l^\pm, l^\pm), (\gamma, \gamma), (\gamma, G), (G, \gamma), (G, G), (q, q), (\bar{q}, \bar{q}), (q, \bar{q})$ or $(\bar{q}, q)$.

$(l^\pm, l^\pm)$ corresponds to semi-inclusive deep inelastic lepton scattering$[2]$, for instance $e^- p \rightarrow e'^- + fast \uparrow hyperon + X$. In this case, $\hat{D}_{NN} = -2\hat{s}\hat{u}/(\hat{s}^2 + \hat{u}^2)$ with $\hat{u}/\hat{s} = -E'_e/E_e$. From the above reactions, the $(G, G)$ one, i.e., $G + \uparrow q \rightarrow G + \uparrow \bar{q}$, has the largest cross section together with a large enough $\hat{D}_{NN}$; it can be realized in $p + \uparrow N \rightarrow high p_T \uparrow hyperon + opposite jet$.

Figure 3. Different routes of the quark lines in Fig. 2. It is understood that the left- and right hand sides of each diagram are sewn line by line. In Fig. 3b, $c$ and $d$ are not necessarily quarks, therefore their lines are not fully displayed.
The experimental advantage of hyperons is that they are self-analysing. The lightest one, Λ, has the theoretical disadvantage (according to the nonrelativistic quark model) that \( \Delta T_{u \rightarrow \Lambda} = \Delta T_{d \rightarrow \Lambda} = 0 \), therefore the two above reactions could not measure \( \Delta T_u(x) \) or \( \Delta T_d(x) \) : Λ is \textit{a priori} not a good \textit{parton polarimeter} for \( u \)- and \( d \)-quarks. This is not so for Σ’s or Ξ’s. There exist also \textit{mesonic} parton polarimeters, such as the \( a_1 \) or ”jet handedness”\,[5,8], involving the measurement of three particles of the jet. In fact, in the case of transverse polarization, two particles would suffice\,[3].

4. Reactions with two final transversely polarized particles

Repeating the crossing procedure leads to the subprocess \( c + d \rightarrow \uparrow a + \uparrow b \).

\( c + d \) may be \( e^+ e^- \), \( \gamma \gamma \), \( G G \), \( q \bar{q} \), \( q q \). \( a \) and \( b \) fragments respectively in hadrons \( A \) and \( B \), whose transverse spins are correlated in the following way (for any couple of transverse vectors \( \hat{n}_A \) and \( \hat{n}_B \)):

\[
< (\hat{\sigma}_A \cdot \hat{n}_A) (\hat{\sigma}_B \cdot \hat{n}_B) > = \hat{n}_B \cdot R_{AB} \hat{n}_A \times \frac{\Delta T_{f \rightarrow C}(z)}{f_{c \rightarrow C}(z)} \times \frac{\Delta T_{f \rightarrow D}(z')}{f_{d \rightarrow D}(z')} \times \hat{A}_{NN}(\hat{\theta}) ;
\]

\( \hat{A}_{NN}(\hat{\theta}) \) is obtained from the inverse subprocess. One possible experiment is \( e^+ e^- \rightarrow \Lambda \bar{\Lambda} \) (in opposite jets) + \( X \), where \( \hat{A}_{NN} = -0.35 \) on the \( Z^0 \) peak\,[5]. Another one is \( pp \rightarrow \Lambda \bar{\Lambda} \) (in opposite jets) + \( X \), via \( G + G \rightarrow s + s \).

5. Conclusion

We have seen that experiments sensitive to quark transverse polarization at leading twist involve two polarized hadrons, which makes them more difficult than longitudinal polarization experiments. They measure the products of two \( \Delta T_q \)'s, or one \( \Delta T_q \times \) one \( \Delta T_f \), or two \( \Delta T_f \)'s. We do not yet know which of the three kinds of experiment will be made first, but we will probably need each of them (the overall sign of all the \( \Delta T \)'s will have to be guessed). \( \Delta T_f(z) \) may also be generalized by jet handedness or some other form of parton polarimeter.

\( \Delta T_q(x) \) and \( \Delta T_f(z) \) are as important as their longitudinal counterparts for the understanding of hadronic structure. At present, the ”spin crisis” is only for longitudinal spin; transverse spin might reserve us a different surprise.

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