TIME REVERSAL INVARIANCE
AND THE TRANSVERSE SPIN STRUCTURE
OF HADRONS\textsuperscript{a}

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The rôle of time reversal invariance in the phenomenology of transverse spin is discussed.

1 Introduction

Time Reversal (TR) invariance is a fundamental constraint on many physical processes. It limits the admissible forms of structure functions, form factors, decay observables, etc. Acting on a momentum and spin eigenstate $|p, s\rangle$, the TR operator $T$ gives

$$T|p, s\rangle = (-1)^{s - s_z} | -p, -s_z\rangle,$$

(1)

where $s$ is the particle’s spin, $s_z$ its third component, and an irrelevant phase has been omitted. An important point, with far-reaching consequences, is that $T$ maps “in” states into “out” states: $T : |\text{in}\rangle \rightarrow |\text{out}\rangle$.

In what follows, we shall discuss the rôle that TR plays in the transverse spin structure of hadrons\textsuperscript{1}. Before entering into the subject, it is worth recalling that the implementation and the implications of TR invariance are sometimes rather subtle, as we are now going to show by a simple example\textsuperscript{2}.

2 A pedagogical example

Consider the decay of a particle of spin $s$ and zero momentum into a state of spin $s'$ and momentum $p'$. Let $O(p'; s, s')$ be an observable. The expectation value of $O$ is

$$\langle O \rangle \sim \sum_{p', s, s'} O(p'; s, s') \langle \text{out}; p', s'| H |s\rangle^2,$$

(2)

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where $H$ is the interaction Hamiltonian responsible for the decay. Inserting a complete set of “out” states, labelled by the total angular momentum $J$ and its third component $m$, the matrix element in (2) becomes

$$\langle \text{out}; p', s'|H|s \rangle = \sum_{Jm} \langle \text{out}; p', s'|\text{out}, J m \rangle \langle \text{out}, J m|H|s \rangle.$$  \hspace{1cm} (3)

It is easy to check, using the TR invariance of $H$, that the phase of $\langle \text{out}, J m|H|s \rangle$ is the phase shift for the channel with angular momentum $J$, that we call $\eta_J$. Thus eq. (3) becomes

$$\langle \text{out}; p', s'|H|s \rangle = \sum_{Jm} \langle \text{out}; p', s'|\text{out}, J m \rangle e^{i\eta_J} |\langle \text{out}, J m|H|s \rangle| \equiv \sum_{Jm} e^{i\eta_J} M(J; p'; s, s') .$$  \hspace{1cm} (4)

In terms of $M$, eq. (2) reads

$$\langle O \rangle \sim \sum_{p', s, s'} O(p'; s, s') \sum_{J, J'} e^{i(J-J')} M(J; p'; s, s') M^*(J'; p'; s, s') .$$  \hspace{1cm} (5)

TR invariance and the unitarity of the $S$-matrix, $S^\dagger S = 1$, imply (for the derivation of this result see the book by Gasiorowicz)\footnote{2}

$$M^*(J; p'; s, s') = M(J; -p'; -s, -s') .$$  \hspace{1cm} (6)

Suppose now that $O$ is odd under TR, that is

$$O(p'; s, s') = -O(-p'; -s, -s') .$$  \hspace{1cm} (7)

Then, with the help of (6), eq. (5) gives

$$\langle O \rangle \sim \sum_{p', s, s'} \sum_{J, J'} \sin(\eta_J - \eta_{J'}) O(p'; s, s') \times M(J; p'; s, s') M(J'; -p'; -s, -s').$$  \hspace{1cm} (8)

This shows that, in spite of the fact that $O$ is $T$-odd, its expectation value does not vanish if $\sin(\eta_J - \eta_{J'}) \neq 0$, which may happen in presence of final state interactions that generate non-trivial phase differences between the various reaction channels.

Thus, the important lesson is that when final-state (or initial-state) non-trivial effects are at work, observables which are naively $T$-odd according to...
their structure in terms of spins and momenta, may give rise to non-zero measurable quantities, without really violating TR invariance.

A noteworthy example is provided by pion-nucleon scattering. Although the correlation

\[(P_\pi \times P_N) \cdot S_N,\]  

is \(T\)-odd in the sense of (7), its vacuum expectation value is known to be non-zero.

3 Semi-inclusive leptoproduction

Our prototype process will be semi-inclusive deep inelastic scattering off a transversely polarised target,

\[l(\ell) + N^\uparrow(P) \rightarrow l'(\ell') + h(P_h) + X(P_X),\]  

whose cross section reads

\[
\frac{d\sigma}{dx dy dz d^2P_{h\perp}} = \frac{\pi \alpha_{em} y}{2 Q^4 z} L_{\mu\nu} W^{\mu\nu}.
\]

Here \(L_{\mu\nu}\) is the usual leptonic tensor of DIS, whereas \(W^{\mu\nu}\) is the hadronic tensor, which is given by, in leading order QCD and leading twist (see Fig. 1 for notations)

\[
W^{\mu\nu} = \sum_a \epsilon_a^2 \int \frac{dk^+ dk^- d^2k_T}{(2\pi)^4} \int \frac{dk^+ dk^- d^2\kappa_T}{(2\pi)^4} \\
\times \delta(k^+ - xP^+) \delta(k^- - P_h^- / z) \delta^2(k_T + q_T - \kappa_T) \text{Tr} [\Phi \gamma^\mu \Xi^\nu],
\]

with \(z = P \cdot P_h / P \cdot q\).

The quark structure of hadrons is incorporated into the correlation matrix \(\Phi\) and the decay matrix \(\Xi\). These matrices are defined as \((i, j)\) are Dirac indices

\[
\Phi_{ij}(k, P, S) = \int d^4 \xi e^{ik \cdot \xi} \langle PS | \bar{\psi}_j(0) \psi_i(\xi) | PS \rangle.
\]

\[
\Xi_{ij}(\kappa; P_h, S_h) = \sum_X \int d^4 \xi e^{i\kappa \cdot \xi} \langle 0 | \psi_i(\xi) | P_h S_h, X \rangle \langle P_h S_h, X | \bar{\psi}_j(0) | 0 \rangle.
\]

\(\Phi\) contains the distribution functions; \(\Xi\) contains the fragmentation functions.

The \(T\)-odd correlations we shall be interested in are similar to (3), but involve the transverse momenta of quarks. They are

\[(k_\perp \times P) \cdot S, \quad (k_\perp \times P) \cdot s,\]  

(15)
Note that, while the first two correlations involve the momentum and/or the spin of the quark inside the target hadron, the third correlation involves the momentum and the spin of the fragmenting quark. According to the general discussion of Sect. 2, the correlations (15) may give rise to observable effects due to some initial-state interactions, whereas (16) may be observable due to final-state interactions.

4 TR invariance and quark distribution functions

Time reversal invariance translates into the following condition on $\Phi$,

$$\Phi^*(k, P, S) = \gamma^5 C \Phi(\tilde{k}, \tilde{P}, \tilde{S}) C^\dagger \gamma^5,$$

where $C = i\gamma^2 \gamma^0$ and the tilde four-vectors are defined as $\tilde{k}^\mu = (k^0, -k)$. This relation is obtained by using

$$T \psi_a(\xi) T^\dagger = -i\gamma_5 C \psi_a(-\tilde{\xi})$$

and $T|PS\rangle = (-1)^{S-S_z}|PS\rangle$. 

Figure 1: Diagram contributing to semi-inclusive DIS in leading order QCD and leading twist.
If we ignore (or integrate over) the transverse motion of quarks, the TR constraint (17) has no effect on the structure of $\Phi$ at leading twist. In this case, the integrated quark–quark correlation matrix $\Phi$

$$\Phi_{ij}(x) = \int \frac{dk}{(2\pi)^4} \Phi_{ij}(k, P, S) \delta \left( x - \frac{k^+}{P^+} \right)$$

reads

$$\Phi(x) = \frac{1}{2} \left\{ f(x) P + \lambda_N \Delta f(x) \gamma_5 P + \Delta_T f(x) P \gamma_5 S_\perp \right\} ,$$

where $f(x)$, $\Delta f(x)$ and $\Delta_T f(x)$ are the unpolarised, the helicity and the transversity distributions, respectively.

At twist 3, on the contrary, the TR property (17) does play a rôle. It forbids, for instance, a pseudoscalar term (which does not contribute to leading twist as it is suppressed by a factor $1/P^+$ in the infinite momentum frame). If we relax the condition (17) – for a justification, see below –, we get a $T$-odd twist–3 correlation matrix, which contains three distribution functions

$$\Phi(x)_{T,R-odd} = \frac{M}{2} \left\{ f_T(x) \varepsilon^{\mu\nu}_1 S_{\perp\mu} \gamma_5 \gamma_\nu - i \lambda_N e_L(x) \gamma_5 + \frac{i}{2} h(x) [\hat{p}, \hat{p}] \right\} ,$$

where $\varepsilon^{\mu\nu}_1 = \varepsilon^{\mu\nu\rho\sigma} P_\rho q_\sigma / P \cdot q$.

As shown by Boer, Mulders and Teryaev there is no need to invoke initial-state interactions to justify the existence of $f_T(x)$, $e_L(x)$ and $h(x)$. These arise as effective distributions related to the multiparton densities which contribute to higher twists. The point is that the twist-3 hadronic tensor contains, besides $\Phi$, a quark-quark-gluon correlation matrix which may have no definite behavior under TR. The condition (17) does not apply to it and $T$-odd distributions are allowed. We emphasize that this mechanism only works at higher twists.

4.1 $T$-odd couple: $\Delta^0_T f$ and $\Delta^0_T f$

Let us return to leading twist. When the transverse motion of quarks inside the target is taken into account, the structure of $\Phi$ is more complicated than (20), and the condition (17) becomes truly restrictive. In particular, it forbids terms in $\Phi$ of the form

$$\varepsilon^{\mu\nu\rho\sigma} \gamma_\mu P_\rho k_{\perp \mu} S_{\perp \sigma} ,$$

$$\varepsilon^{\mu\nu\rho\sigma} \gamma_5 \sigma_{\mu \nu} P_\rho k_{\perp \sigma} ,$$

which give rise to two $k_{\perp}$-dependent TR-odd distribution functions, that we call $\Delta^0_T f$ and $\Delta^0_T f$. The former is related to the number density of unpolarised
quarks in a transversely polarised nucleon; the latter measures the transverse polarisation of quarks in an unpolarised hadron. If we call $P_{a/p}(x, k_\perp)$ the probability to find a quark $a$ with momentum fraction $x$ and transverse momentum $k_\perp$ in the target proton, we have

$$\frac{1}{|P, \pm\rangle}$$

are the momentum-helicity eigenstates of the proton.

$$P_{a/p}^\uparrow(x, k_\perp) - P_{a/p}^\downarrow(x, -k_\perp) = \text{Im} \int \frac{dy^- d^2y_\perp}{2(2\pi)^3} e^{-ixP^+ y^- + ik_\perp \cdot y_\perp} \langle P, -|\bar{\psi}_a(0, y^-, y_\perp)^+\psi_a(0)|P, + \rangle$$

$$\equiv \frac{(k_\perp \times P) \cdot S_\perp}{|k_\perp \times P||S_\perp|} \Delta T_0^f(x, k_\perp^2),$$

(24)

and

$$P_{a^+/p}(x, k_\perp) - P_{a^+/p}(x, -k_\perp) = \int \frac{dy^- d^2y_\perp}{2(2\pi)^3} e^{-ixP^+ y^- + ik_\perp \cdot y_\perp} \langle P, \bar{\psi}_a(0, y^-, y_\perp)i\sigma^2\gamma_5\psi_a(0)|P \rangle$$

$$\equiv \frac{(k_\perp \times P) \cdot s_\perp}{|k_\perp \times P||s_\perp|} \Delta T_0^f(x, k_\perp^2).$$

(25)

(The transverse polarisation of the quarks and of the proton is denoted by arrows and assumed to be directed along the $y$-axis.)

In the literature one often finds two other functions, $f_{T}^\perp$ and $h_{T}^\perp$, related to $\Delta T_0^f$ and $\Delta T_0^f$ by

$$\Delta T_0^f(x, k_\perp^2) = -2 \frac{|k_\perp|}{M} f_{T}^\perp(x, k_\perp^2),$$

(26)

$$\Delta T_0^f(x, k_\perp^2) = - \frac{|k_\perp|}{M} h_{T}^\perp(x, k_\perp^2).$$

(27)

The distribution $\Delta T_0^f$ was first introduced by Sivers and its phenomenological applications were investigated by several authors. The distribution $\Delta T_0^f$ was studied by Boer and Mulders. Their $T$-odd character can be checked by direct inspection. Using the standard action of $T$ on quark fields, i.e. eq. (18), it is easy to show that the matrix elements in (24,25) change sign under $T$, and therefore the corresponding distributions must vanish (this was first pointed out by Collins).

Let us now comment on the physical meaning of the distributions we have just introduced. One may legitimately wonder whether $T$-odd quantities, such as $\Delta T_0^f$ and $\Delta T_0^f$, make any sense at all. In order to justify the existence of
these quantities, their proponents advocate initial-state hadronic interactions, which prevent implementation of time-reversal invariance via the condition \( (17) \). The idea is that the colliding particles interact strongly with non-trivial relative phases. If this is correct, \( \Delta_T^0 f \) and \( \Delta_T^0 f \) should only be observable in reactions involving two initial hadrons (Drell-Yan processes, hadron production in proton-proton collisions, etc.), not in lepton production.

The Sivers function \( \Delta_T^0 f \) may account for the observed single-spin asymmetry in transversely polarised pion hadroproduction (the so-called Sivers effect, see Sect. 6). The distribution \( \Delta_T^0 f \) has been used by Boer to explain, at leading-twist level, an anomalously large \( \cos 2\phi \) term in the unpolarised Drell–Yan cross section. Introducing initial–state \( T \)-odd effects, the unpolarised Drell–Yan cross section acquires indeed a \( \cos 2\phi \) contribution proportional to the product \( \Delta_T^0 f \times \Delta_T^0 f \).

The real difficulty about the \( T \)-odd distributions is that no initial-state interaction mechanism is known which can produce such things as \( \Delta_T^0 f \) and \( \Delta_T^0 f \). Therefore their existence is – to say the least – highly questionable.

A different way of looking at the \( T \)-odd distributions is presently under investigation. It is based on a “non-standard” time reversal for particle multiplets, which turns out to be a good symmetry in chiral quark models of the nucleon. Equation (18) is replaced by

\[
T \psi_a(\xi) T^\dagger = -i(\tau_2)_{ab} \gamma^5 C \psi_b(-\bar{\xi}),
\]

where \( \tau \) is the isospin operator. The time inversion in (28) relates different components of the flavor multiplet and consequently (24) and (25) do not vanish any longer once \( TR \) invariance is imposed (via (28)). If this mechanism is correct, the \( T \)-odd distributions should also be observable in semi-inclusive lepton production. A conclusive statement on the matter will only be made by experiments.

5 TR invariance and quark fragmentation functions

In the fragmentation process one cannot naively impose a condition similar to (17), that is

\[
\Xi^*(\kappa, P_h, S_h) = \gamma^5 C \Xi(\bar{\kappa}, \bar{P}_h, \bar{S}_h) C^\dagger \gamma^5.
\]

In the derivation of (17) the simple transformation property of the nucleon state \( |P S \rangle \) under \( T \) is crucial. However, \( \Xi \) contains \( |P_h S_h, X \rangle \) which are “out” states. Under time reversal they do not simply invert their momenta and spins but transform into “in” states

\[
T |P_h S_h, X; \text{out} \rangle \propto |\bar{P}_h \bar{S}_h, \bar{X}; \text{in} \rangle.
\]
These may differ non trivially from $|\tilde{P}_h\tilde{S}_h, \tilde{X}; \text{out}|$, due to final-state interactions, which can generate relative phases between the various channels of the $|\text{in}\rangle \rightarrow |\text{out}\rangle$ transition. As a consequence, a term in $\Xi$ of the form

$$e^{\mu\nu\rho\sigma} \gamma_\delta \sigma_{\mu\nu} P_\rho \kappa_T \sigma$$

is not forbidden by time reversal invariance, and generates a $T$-odd fragmentation function, $\Delta_T^0 D$, given by

$$\mathcal{N}_{h/\alpha\gamma}(z, \kappa'_T) - \mathcal{N}_{h/\alpha\downarrow}(z, \kappa'_T) = \frac{(\kappa_T \times P_h) \cdot s'}{|\kappa_T \times P_h| |s'|} \Delta_D^0(z, \kappa'^2_T),$$

where $\kappa'_T = -z\kappa_T$. $\Delta_T^0 D$ is responsible for the the so-called Collins effect, i.e., non-zero azimuthal asymmetries in single-inclusive production of unpolarised hadrons at leading twist. In Mulders’ classification, a function $H_{1\perp}$ is introduced, which is related to $\Delta_D^0 T$ by

$$\Delta^0_T(z, \kappa'^2_T) = \frac{\kappa_T |H_{1\perp}(z, \kappa'^2_T)|}{M_h}.$$

The factor in front of $\Delta_T^0 D$ in (32) is the sine of the azimuthal angle between the spin vector and the momentum of the fragmenting quark, the so-called “Collins angle” $\Phi_C$.

Just to see in practice how the $T$-odd fragmentation function $\Delta_T^0 D$ may arise from non trivial final–state interactions, let us assume that a quark fragments into an unpolarised hadron, leaving, as a remnant, a pointlike scalar diquark. If we describe the hadron $h$ by a plane wave,

$$\psi_h(x) \sim u(P_h) e^{i P_h \cdot x},$$

it is easy to show that the fragmentation matrix $\Xi$ is

$$\Xi(\kappa, P_h) \sim \frac{-i}{\hat{k} - m} u(P_h) \frac{1}{\hat{k} - m} \frac{i}{\hat{k} + m} \frac{\hat{k} + m}{\kappa^2 - m^2} (P_h + M_h) \frac{\hat{k} + m}{\kappa^2 - m^2},$$

where $m$ is the quark mass and we have omitted some inessential factors. From (33) we cannot extract a term of the type (31) (hence, producing $\Delta_T^0 D$). Let us now suppose that a residual interaction of $h$ with the intermediate state generates a phase in the hadron wave function. If, for instance, we make in (35) the replacement (assuming only two fragmentation channels)

$$u(P_h) \rightarrow u(P_h) + e^{i x \cdot \hat{k}} u(P_h),$$

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$$u(P_h) \rightarrow u(P_h) + e^{i x \cdot \hat{k}} u(P_h),$$

and
by a little algebra one can show that $\Xi$ acquires a term

$$\frac{M_h}{\kappa^2 - m^2} \sin \chi \, \varepsilon^{\mu \nu \rho \sigma} \gamma_5 \sigma_{\mu \nu} P_\rho k_{\perp \sigma}. \quad (37)$$

Therefore, if the interference between the fragmentation channels produces a non–zero phase $\chi$, a $T$-odd contribution may appear.

Bacchetta et al. have recently shown that in a chiral quark model with pseudoscalar couplings the Collins fragmentation function is generated by one-loop self-energy and vertex correction diagrams.

However, as argued by Jaffe, Jin and Tang, the proliferation of channels and the sum over $X$ might ultimately lead to an overall cancellation of the relative phases between the channels, and to the vanishing of the Collins function. If this is true (and only experiments will provide a definite answer), then, in order to observe a $T$-odd correlation in the fragmentation process, one should rather consider correlated variables belonging to physical particles with known interactions. This suggests to return to a quantity exactly like (9), namely

$$(P_1 \times P_2) \cdot S, \quad (38)$$

where $P_1$ and $P_2$ are the momenta of two final-state hadrons. Two-hadron leptonproduction,

$$l(\ell) + N^+(P) \rightarrow l'(\ell') + h_1(P_1) + h_2(P_2) + X(P_X). \quad (39)$$

has been proposed and studied as a potential source of information about transversity and $T$-odd correlations. In the decay matrix the term proportional to (38) contains a fragmentation function $\Delta_T I(z, \xi, M^2_h)$, where $M_h = P_h^2 = (P_1 + P_2)^2$ and $\xi = P \cdot P_1 / P \cdot P_h$. In the specific case of $\pi^+\pi^-$ production, $\Delta_T I$ arises from the interference between the $s$- and $p$-wave of the pion system, which is known from the experiment to be non zero.

6 Single-spin asymmetries

As they involve transversely polarised quarks in unpolarised hadrons, or vice-versa, the $T$-odd distribution and fragmentation functions may give rise to single-spin transverse asymmetries in lepto- and hadroproduction.

In 1991, the E704 experiment at Fermilab discovered a sizeable single-spin asymmetry in inclusive pion hadroproduction with a transversely polarised proton (Fig. 3). This result, which cannot be explained by perturbative QCD in leading twist, may be attributed either to the $T$-odd distribution function $\Delta^I_0 f$
Figure 2: Fit of the data on $A_N^\pi$ for the process $p^+p \rightarrow \pi X$ assuming that only Collins effect is active (Ref. 13); the upper, middle, and lower sets of data and curves refer to $\pi^+$, $\pi^0$ and $\pi^-$, respectively. (Sivers effect) or to the $T$-odd fragmentation function $\Delta_T^{0,f}$ (Collins effect)\textsuperscript{1}

In the former case one has

$$d\sigma^+ - d\sigma^- \sim \sum_{abc} \int dx_a \, dx_b \, d^2k_T \, \Delta_0^{T,f}(x_a, k_T^2) \, f_0(x_b) \, d\hat{\sigma} \, D_c(z), \quad (40)$$

where $d\hat{\sigma}$ is a partonic cross section and $D(z)$ is the familiar unpolarised fragmentation function. The Collins mechanism gives

$$d\sigma^+ - d\sigma^- \sim \sum_{abc} \int dx_a \, dx_b \, d^2k_T \, \Delta_T f_a(x_a, k_T^2) \, f_b(x_b) \, \Delta_T \hat{\sigma} \, \Delta_0^{T,f}(z, k_T^2), \quad (41)$$

where $\Delta_T \hat{\sigma}$ is a partonic double-spin asymmetry.

Fig. 2 shows the asymmetry predicted by Anselmino et al.\textsuperscript{1} using eq. (41) and a simple parametrisation of the Collins function. An equally good description is obtained by means of eq. (40). An alternative theoretical picture to Collins and Sivers mechanisms is based on higher-twist, non $T$-odd, distribution and fragmentation functions.\textsuperscript{1} The investigation of the $p_T$ dependence of the process would clearly help to distinguish between leading-twist and higher-twist effects.

The first (preliminary) measurements of single-spin transverse asymmetries in pion leptoproduction have been presented two years ago by HERMES\textsuperscript{2}.

\textsuperscript{2}An explanation in terms of $\Delta_0^{T,f}$ is also possible.
The HERMES result is shown in Fig. 3. The sin $\phi$ contribution to the asymmetry (where $\phi$ is the azimuthal angle of the produced pion) has the form

$$ A_T \sim \Delta_T f(x) \Delta^0_T D(z, P_{\pi \perp}) \sin \phi. $$

(42)

A fit of the data, based on (42) and on two different assumptions for the transversity distribution $\Delta_T f$, is displayed in Fig. 3. As one can see, the agreement is fairly good (the HERMES data are also well reproduced by a light-cone quark model). From the result on $A^T$ one can derive a lower bound for the quark analysing power $\Delta^0_T D/D$, namely

$$ \frac{|\Delta^0_T D|}{D} > 0.20, \quad z \geq 0.2. $$

(43)

Concluding this phenomenological account, it is fair to say that the present scarcity of data, their uncertainties and our ignorance of most of the quantities involved in the process make the entire matter still rather vague. More, and more precise, measurements are clearly needed to get a better understanding.

7 Perspectives

In the next few years, the upgraded HERMES experiment at HERA and the COMPASS experiment at CERN (which upgrades SMC) will provide more ac-
curate measurements of the single-spin transverse asymmetry in semi-inclusive pion production and, hopefully, the first measurements of the transverse asymmetry in two-hadron production. This should allow us to achieve two goals: 

i) to extract for the first time the transversity distributions of the nucleon and

ii) to reveal in a clear way possible $T$-odd effects. In order to disentangle mechanisms of different nature giving rise to single-spin asymmetries, the study of the $Q^2$ dependence of the processes will be crucial.

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