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Could large *CP*-violation be detected in polarized proton collisions at RHIC?

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The measurable asymmetries due to *CP*- and/or *T*-violation in charged and neutral current leptoproduction by polarized protons are discussed.

Just in months ahead, the first high luminosity collisions of two polarized proton beams are expected to occur at RHIC in BNL at $\sqrt{s}$ up to 500 GeV, bringing a new quality to the collider physics. In the collisions of polarized particles, the presence of two axial vectors of initial polarizations, fully controlled by experimenters, may dramatically increase the number of available for tests *T*-odd correlations which could relatively easily be measured. The *CP*/*T*-violation mechanism behind these correlations could virtually be anywhere and everywhere [1,2].

In this paper we will show two examples of measurable *T*-odd correlations for hadronic leptoproduction via vector $W^{\pm}$- and Z^0-boson exchange:

$$q\overline{q} \to W^{\pm} \to l\overline{l} \quad \text{and} \quad q\overline{q} \to Z^0 \to l\overline{l}\ . \tag{1}$$

In the lowest order, processes (1) are represented by the usual *s*-channel annihilation graphs. The *CP*- and *T*-violation may occur in either or both of two vertices. In this paper, for the sake of simplicity, the presence of *T*-odd phases has been assumed in the quark sector only, and the usual (V-A)-interactions were kept for lepton coupling to gauge bosons. To carry out some particular calculations, the phenomenological lagrangian [2] has been used. For the charged current $q_u q_d W$-coupling, this lagrangian was as follows:

$$L_c = \frac{g}{2\sqrt{2}}\Big\{W_\mu^- \overline{q}_d \gamma^\mu (f_1^+ + f_1^- \gamma_5) q_u + \frac{1}{\Lambda}\big[\partial_\nu W_\mu^- \overline{q}_d \sigma^{\mu\nu} (f_2^+ + f_2^- \gamma_5) q_u\big] + \text{h.c.}\Big\} \tag{2}$$

where g is a coupling constant, presumably on the order of the electroweak one, Λ is the energy scale of the full strength "tensor"[a] interactions. The notations q_u and q_d are for the "upper" (u and c)[b] and "lower" (d, s, and b) quarks, respectively. The *CP*-symmetry of model (2) is broken if any or all formfactors $f_i^{\pm}$ are complex. In the neutral current lagrangian, L_n, of type (2) for qqZ-interactions[c], three formfactors, $f_1^{\pm}$ and f_2^{+}, are real. The *CP*-violation may occur only due to "tensor" coupling with purely imaginary $f_2^- \neq 0$.

In "2→2"–type processes (1), four *T*-odd correlations could be built, using two axial vectors, $\boldsymbol{\zeta}_q$ and $\boldsymbol{\zeta}_{\overline{q}}$, of the initial quark polarizations and two independent momentum vectors of the initial

[a] The shortcuts "tensor" and "vector" are used for the couplings with and without derivatives ∂_ν, respectively.
[b] t-quark is virtually not reachable at RHIC
[c] ... of a truly neutral $q\overline{q}$-pair, consisting of a fermion q and its antiparticle.

quark, $\boldsymbol{p} \equiv \boldsymbol{p_q}$, and of the final lepton, $\boldsymbol{k} \equiv \boldsymbol{k}_{e^-}$ or $\boldsymbol{k_\nu}$. These correlations are: $(\boldsymbol{k}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{p}])$, $(\boldsymbol{k}\cdot[\boldsymbol{\zeta_{\overline{q}}}\times\boldsymbol{p}])$, $(\boldsymbol{k}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{\zeta_{\overline{q}}}])$, and $(\boldsymbol{p}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{\zeta_{\overline{q}}}])$. Apparently, for either of the correlations above to be nonzero, at least one initial quark must be transversely polarized. However, at $\sqrt{\hat{s}}$ in the range of W- and Z-masses, $M_{W,Z} = 80$–90 GeV, all single-spin asymmetries are suppressed by a factor of $m_{q,l}/\sqrt{\hat{s}}$ with quark and lepton masses, $m_{q,l} \leq 5$ GeV. Moreover, all T-odd double-spin asymmetries with one quark polarized transversely and the other one polarized longitudinally are also suppress by at least the same factor.

In model (2), the tree-level cross section for the transversely polarized quark and antiquark annihilation in their c.m. system of reference is:

$$\frac{d\hat{\sigma}}{d\Omega} \simeq \frac{g^4\hat{s}(\mid M^V_{fi}\mid^2 + \hat{s}\mid M^T_{fi}\mid^2/\Lambda^2)}{64\left[(\hat{s}-M^2_{W,Z})^2 + \frac{\Gamma^2_{W,Z}}{2}(\hat{s}+M^2_{W,Z}) + \frac{\Gamma^4_{W,Z}}{16}\right]} \quad \text{with} \tag{3}$$

$$\begin{aligned}\mid M^V_{fi}\mid^2 = {} & \frac{\mid f_1^+ + f_1^-\mid^2}{4}[1+\boldsymbol{n_p}\cdot\boldsymbol{n_k}]^2 + \frac{\mid f_1^+ - f_1^-\mid^2}{4}[1-\boldsymbol{n_p}\cdot\boldsymbol{n_k}]^2 + \\ & + (\mid f_1^+\mid^2 - \mid f_1^-\mid^2)\{(\boldsymbol{\zeta_q}\cdot\boldsymbol{n_k})(\boldsymbol{\zeta_{\overline{q}}}\cdot\boldsymbol{n_k}) - \tfrac{1}{2}(\boldsymbol{\zeta_q}\cdot\boldsymbol{\zeta_{\overline{q}}})[1-(\boldsymbol{n_p}\cdot\boldsymbol{n_k})^2]\} \\ & \pm \mathrm{Im}(f_1^+ f_1^{*-})\{\boldsymbol{n_k}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{n_p}](\boldsymbol{\zeta_{\overline{q}}}\cdot\boldsymbol{n_k}) + \boldsymbol{n_k}\cdot[\boldsymbol{\zeta_{\overline{q}}}\times\boldsymbol{n_p}](\boldsymbol{\zeta_q}\cdot\boldsymbol{n_k})\}\end{aligned} \tag{4}$$

$$\begin{aligned}\mid M^T_{fi}\mid^2 = {} & \frac{1}{2}\{1-(\boldsymbol{n_p}\cdot\boldsymbol{n_k})^2\}\times\{\mid f_2^+\mid^2 + \mid f_2^-\mid^2 - \\ & -(\mid f_2^+\mid^2 - \mid f_2^-\mid^2)(\boldsymbol{\zeta_q}\cdot\boldsymbol{\zeta_{\overline{q}}}) + 2\,\mathrm{Im}(f_2^+ f_2^{*-})(\boldsymbol{n_p}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{\zeta_{\overline{q}}}])\}\end{aligned} \tag{5}$$

where $\Gamma_{W,Z}$ is for the W- or Z-peak width, the unit-vector $\boldsymbol{n_p} = \boldsymbol{p}/\mid\boldsymbol{p}\mid$, and $\boldsymbol{n_k} = \boldsymbol{k}/\mid\boldsymbol{k}\mid$. The upper and lower signs before the last term in Eq. (4) correspond to W^+ and W^- productions, respectively. Only the main contributions are kept in Eqs. (3)–(5), neglecting the "vector–tensor" interference as well as all other terms suppressed by powers of $m_{q,l}/\sqrt{\hat{s}}$.

The T-odd correlations of the "vector" coupling could be detected as a transverse "quadrupole" azimuthal anisotropy of lepton production. In two CP-conjugate processes of $W^\pm$-production, these "true" CP-odd asymmetries are of the opposite signs. This makes them distinguishable from "spurious" CP-even ones because the latter do not change signs after CP-conjugation. Therefore, if this anisotropy is detected in the neutral current annihilation[c], it could never be "true", but only the "spurious" one due to some CP-even initial and/or final state interactions.

CP-violation in "tensor" coupling makes the cross section dependent on the sign of product $(\boldsymbol{n_p}\cdot[\boldsymbol{\zeta_q}\times\boldsymbol{\zeta_{\overline{q}}}])$ with the measurable $\Delta\sigma_\perp = \sigma^R_\perp - \sigma^L_\perp$ where cross sections $\sigma^{R,L}_\perp$ are for the "right" and "left" mutual orientations of vectors $\boldsymbol{\zeta_q}$, $\boldsymbol{\zeta_{\overline{q}}}$, and $\boldsymbol{n_p}$, respectively. The "true" CP-odd $\Delta\sigma_\perp \propto \mathrm{Im}(f_2^+ f_2^{*-})$ should be of the same sign in W^+ and W^- productions, but "spurious" ones change signs after CP-conjugation. In the neutral current annihilation[c], neither CP-even theory can generate a nonzero $\Delta\sigma_\perp$. Therefore, a detection of a nonzero neutral-current $\Delta\sigma_\perp$ would be an unambiguous evidence of CP-violation.

To detect T-odd asymmetries (4) and (5), the directions of motion of the incident quark and antiquark have to be known. In pp-collisions, these asymmetries integrated over the full phase space will obviously be zero. However, if a valence quark participated in the CP-odd process of W- or Z-production, the produced boson would likely be moving in the direction of the incident "hard" valence quark rather then in the direction of a "soft" sea antiquark. As a result, the nonzero T-odd asymmetries might separately be detectable in the forward and backward hemispheres. In the most favorable case of CP-violating udW-interactions, the "true" CP-odd correlations in $W^\pm$-production could even be distinguishable from the "spurious" ones.

An expected RHIC sensitivity to the asymmetries above at pp-level would be $\sim 10^{-2}$–10^{-3}. It is yet to be studied, how this sensitivity should be transfered back to the quark level, as well as the limitations to CP-odd amplitudes, arising from already accomplished experiments.

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