Disentangling Non-Standard Model $T$-Violating Sources in Exclusive Semileptonic $B$ Decays

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Measurements of the polarization of the lepton and $D^*$ in the exclusive semileptonic $B$ decays, $B \to D(\pi)$ and $B \to D^*(\pi)$, can be used to separate and identify the non-standard model sources of $T$ violation. These $T$-odd effects, estimated in both supersymmetric and non-supersymmetric models, could be within the reach of the planned $B$ factories.

1 Introduction

The transverse muon polarization in the $K_{\mu3}^+$ decay has long been known to serve as a probe of non standard model (SM) $T$-violating scalar interactions \cite{1,2}. For the exclusive semileptonic $B$ decays $B \to D(\pi)$ and $B \to D^*(\pi)$, $T$-odd polarization observables (TOPO’s) can also be constructed by using the spin vectors of the lepton and/or vector meson $D^*$. These observables receive negligible contributions from the standard model, and can be used to differentiate between the possible structures of non-SM $T$-violating sources \cite{3}, a feature which is not available for the inclusive semileptonic $B$ decays \cite{4,5}. In particular, it will be shown that transverse polarizations of the $\tau$ lepton in $B \to D$ and $B \to D^*$ decays are respectively sensitive to phases in the effective scalar and pseudoscalar interactions, whereas the $T$-odd $D^*$ polarization is sensitive to an effective right-handed current effect. The Lorentz structures of the new physics can thus be uniquely identified. For the purpose of illustration, several classes of models are shown to give rise to large $T$-odd effects \cite{6}.

2 General Analysis

We start by deriving the model-independent results for the TOPO’s.

2.1 Four-Fermi Interactions

The physics of semileptonic $B$ decays can be written in terms of general four-Fermi interactions,

\[
\mathcal{L} = -\frac{G_F}{\sqrt{2}} V_{tb} \bar{c} \gamma_\alpha (1 - \gamma_5) b \bar{\ell} \gamma_\alpha (1 - \gamma_5) \nu + G_S \bar{c} b \bar{\ell} (1 - \gamma_5) \nu + G_P \bar{c} b \bar{\ell} (1 + \gamma_5) \nu + G_R \bar{c} b \bar{\ell} (1 - \gamma_5) \nu + h.c., \quad (1)
\]
where $G_F$ is the Fermi constant, $V_{cb}$ is the relevant CKM matrix element, and $G_S$, $G_P$ and $G_R$ denote the strengths of the non-SM interactions due to scalar, pseudoscalar and right-handed current exchange respectively. Tensor effects are negligible in most cases and will not be considered.

It is convenient to introduce three dimensionless parameters which are directly involved in the decay amplitude,

$$\Delta_{S,P} = \frac{\sqrt{2}G_{S,P}G_FV_{cb}}{m_b \pm m_c m_l}, \quad \Delta_R = \frac{\sqrt{2}G_R}{G_FV_{cb}},$$

where the $-$ and $+$ signs correspond to $\Delta_S$ and $\Delta_P$ respectively, and $m_b$, $m_c$, and $m_l$ are the quark and lepton masses. The phases in these $\Delta$ parameters could lead to observable $CP$-violating effects.

### 2.2 $\tau$ polarization

The transverse lepton polarization can be best studied for the heaviest lepton, the $\tau$. It is defined as

$$P_{\tau} = \frac{s_{\tau} \cdot \langle p_D^{(\ast)} \times p_\tau \rangle}{|p_D^{(\ast)} \times p_\tau|},$$

where $s_\tau$ is the spin vector of the $\tau$. For numerical estimates, we use for the form factors the leading order results in heavy quark effective theory, and take the Isgur-Wise function to be $\xi(w) = 1 - 0.75(w - 1)$ as the average value of current data.

For the $B \to D\tau\bar{\nu}$ decay, the transverse $\tau$ polarization depends on an effective scalar interaction. Its value when averaged over the whole phase space is

$$P_{\tau}^{(B)} = -\bar{\sigma}_D^{} Im\Delta_S = -0.22 \times Im\Delta_S,$$

where the coefficient is proportional to the mass ratio $m_\tau/m_B$.

The $\tau$ polarization in the $B \to D^*\tau\bar{\nu}$ decay is sensitive to an effective pseudoscalar interaction. And its average is

$$P_{\tau}^{(D^*)} = -\bar{\sigma}_D^{} Im\Delta_P = -0.068 \times Im\Delta_P.$$

Note that $\bar{\sigma}_D^{}$ is about a factor of three smaller than $\bar{\sigma}_D^{}$. This is because effectively only one of the three polarization states of the $D^*$, the longitudinal polarization, contributes to the transverse $\tau$ polarization.
2.3 $D^*$ polarization

We now construct TOPO’s for $B \to D^*\pi$ decay using the $D^*$ polarization vector $\epsilon$. Since we are not measuring the spin of the lepton, we can take the $\ell = e, \mu$ modes which have a larger branching ratio than the $\tau$ mode. The TOPO’s constructed can be shown to have a one-to-one correspondence with certain $T$-odd momentum correlations in the four-body final state $B \to D^*(D\pi, D\gamma)\ell\nu$.

Working in the $B$ rest frame, we denote the three-momenta of the $D^*$ and $\ell$ by $p_{D^*}$ and $p_\ell$, and define three orthogonal vectors $\vec{n}_1 \equiv (p_{D^*} \times p_\ell) \times p_{D^*}$, $\vec{n}_2 \equiv \frac{p_{D^*} \times p_\ell}{|p_{D^*} \times p_\ell|} p_{D^*}$, and $\vec{n}_3 \equiv \frac{p_{D^*} \times m_{D^*}}{|p_{D^*} \times m_{D^*}|}$. The vector $\vec{n}_3$ has been chosen such that the constraint $\epsilon^2 = -1$ becomes symmetric in the $\vec{n}$’s; i.e. $(\epsilon \cdot \vec{n}_1)^2 + (\epsilon \cdot \vec{n}_2)^2 + (\epsilon \cdot \vec{n}_3)^2 = 1$. It is useful to note that the $D^*$ polarization projection transverse to the decay plane, $\epsilon \cdot \vec{n}_2$, is $T$-odd, and that the projections inside the decay plane, $\epsilon \cdot \vec{n}_1$ and $\epsilon \cdot \vec{n}_3$, are $T$-even.

A measure of the $T$-odd correlation involving the $D^*$ polarization can be defined as

$$P_{D^*} \equiv \frac{d\Gamma - d\Gamma'}{d\Gamma_{total}} = \frac{2d\Gamma_{T-odd}}{d\Gamma_{total}},$$

where $d\Gamma'$ is obtained by performing a $T$ transformation on $d\Gamma$, $d\Gamma_{T-odd}$ is the $T$-odd piece in the partial width, and $d\Gamma_{total}$ is the partial width summed over $D^*$ polarizations.

The $D^*$ polarization observables can now be shown to depend on right-handed current interactions, and to involve two structures which can be separated. Simply averaging over the whole phase space keeps only the first polarization structure,

$$P_{D^*}^{(1)} \approx 0.51 \times (\epsilon \cdot \vec{n}_1)(\epsilon \cdot \vec{n}_2)Im\Delta_R.$$  

(7)

The second polarization structure may be separated out by making use of a symmetry under the reflection of the lepton energy. This procedure gives the second TOPO involving the $D^*$ polarization,

$$P_{D^*}^{(2)} \approx 0.40 \times (\epsilon \cdot \vec{n}_2)(\epsilon \cdot \vec{n}_3)Im\Delta_R.$$  

(8)

Complementary measurements of both observables may then be used to provide a consistency check regarding the possible existence of a right-handed current.

The main results of this section are summarized in Table 1.
Table 1: TOPO’s and effective four-Fermi interactions

|        | $\text{Im}\Delta_S$ | $\text{Im}\Delta_P$ | $\text{Im}\Delta_R$ |
|--------|---------------------|---------------------|---------------------|
| $P_{\tau}^{(D)}$ | $\checkmark$       | 0                   | 0                   |
| $P_{\tau}^{(D^*)}$ | 0             | $\checkmark$         | 0                   |
| $P_{D^*}^{(1,2)}$ | 0             | 0                   | $\checkmark$         |

3 Model Estimates

In Table 2, the maximal $T$-odd polarization effects are listed in both super-symmetric (SUSY) and non-SUSY models. The detailed calculations can be found in Ref. 6.

- It has been noted 9 that squark generational mixings between $\tilde{t}_R$ and $\tilde{c}_R$ can give rise to a double enhancement, due to $m_t$ and due to large mixing, and can lead to large $T$-violating effects in $B$ decay.

- For $R$-parity breaking models, bounds from flavor changing neutral current processes and lepton universality constrain the $T$-odd effects to be at most a few percent. There is no induced right-handed current (RHC) at tree level.

- In multi-Higgs-doublet models, the bound from $B \to X\tau\nu$ does not rule out a large polarization effect. However, there is no RHC induced at tree level.

- In leptoquark models, large $T$-odd effects are found to be possible with effective scalar and pseudoscalar four-Fermi interactions.

- In left-right symmetric models, if one does not impose manifest or pseudo-manifest left-right symmetry, the constraint on the $W_L-W_R$ mixing will be less stringent. Sizable RHC can then give rise to a $D^*$ polarization effect as large as 8%.

4 Summary

The TOPO’s constructed for the exclusive semileptonic $B$ decays have been shown to probe separately effective scalar, pseudoscalar, and right-handed cur-
Table 2: Contributions to the effective four-Fermi interactions and to the various TOPO’s from SUSY with squark intergenerational mixing, SUSY with $R$-parity violation, the three Higgs-doublet model (3HDM), leptoquark models, and left-right symmetric models (LRSM’s).

|                | squark mixing | $R$ SUSY | 3HDM | Leptoquarks | LRSM |
|----------------|---------------|----------|------|-------------|------|
| $\Delta S$     | $\checkmark$  | $\checkmark$ | $\checkmark$ | $\checkmark$ | 0    |
| $\Delta P$     | $\checkmark$  | $\checkmark$ | $\checkmark$ | $\checkmark$ | 0    |
| $\Delta R$     | $\checkmark$  | 0        | 0    | 0           | 0    |
| $|P_{T}^{(D)}|$  | 0.35          | 0.05     | $\sim 1$ | $\sim 1$   | 0    |
| $|P_{T}^{(D^*)}|$ | 0.05          | 0.008    | 0.3   | 0.2         | 0    |
| $|P_{D_{r}}^{(1)}|$ | 0.02          | 0        | 0     | 0           | 0.08 |
| $|P_{D_{r}}^{(2)}|$ | 0.016         | 0        | 0     | 0           | 0.06 |

Recent interactions. They receive sizable contributions from a variety class of models, and could be detectable at the planned $B$ factories.

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