T violation in $B \to VV$ Decays in the SM and Beyond

Alakabha Datta$^a$ and David London $^b$

$^a$ Department of Physics, University of Toronto,
60 St. George Street, Toronto, ON, Canada M5S 1A7

$^b$ Laboratoire René J.-A. Lévesque, Université de Montréal,
C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C 3J7

In this talk, we describe T-violating triple-product correlations (TP’s) in $B \to V_1V_2$ decays. We point out that TP’s in the SM are generally tiny. It is only in a few decays with excited vector mesons in the final state that measurable TP’s may be obtained. On the other hand, TP’s in models beyond the SM can be large, and hence TP correlations are excellent probes of new physics.

1 Triple Products

The study of CP violation in the $B$ system is very useful for understanding the flavour sector of the standard model (SM) and for searching for new physics. Most CP-violation studies involve mixing-induced CP-violating asymmetries in neutral $B$ decays and direct CP asymmetries [1]. In any local and Lorentz-invariant field theory, CP violation implies T violation from CPT conservation. The study of T violation can therefore yield further information on CP and T-violating phases in the SM or in models of new physics.

In general T violation is studied via triple-product correlations. These triple products (TP’s) take the form $v_1 \cdot (v_2 \times v_3)$, where each $v_i$ is a spin or momentum, and are odd under time reversal. One can define a TP asymmetry as

$$A_T = \frac{\Gamma(v_1 \cdot (v_2 \times v_3) > 0) - \Gamma(v_1 \cdot (v_2 \times v_3) < 0)}{\Gamma(v_1 \cdot (v_2 \times v_3) > 0) + \Gamma(v_1 \cdot (v_2 \times v_3) < 0)}$$

(1)

where $\Gamma$ is the decay rate for the process in question.

Unfortunately, strong phases can produce a nonzero value of $A_T$, even if the weak phases are zero (i.e. there is no CP violation). Hence, to search for a true T-violating signal one should compare $A_T$ with $\tilde{A}_T$, where $\tilde{A}_T$ is the T-odd asymmetry measured in the CP-conjugate decay process [2].

Like CP asymmetries, TP asymmetries are nonzero only if there are two interfering decay amplitudes. However, there is an important difference between the two. Denoting $\phi$ and $\delta$ as the relative weak and strong phases, respectively, between the two interfering amplitudes, the signal for direct CP violation can be written

$$A^{dir}_{CP} \propto \sin \phi \sin \delta$$

(2)

while that for the (true T-violating) TP asymmetry is given by

$$A_T \propto \sin \phi \cos \delta$$

(3)

Since strong phases in $B$ decays are expected to be small due to the heavy $b$-quark mass, it is likely that triple-product asymmetries will be easier to measure than direct CP asymmetries.

In the rest frame of the $B$, the TP for the process $B \to V_1V_2$ takes the form $\vec{q} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$, where $\vec{q}$ is the momentum of one of the final vector mesons, and $\vec{\varepsilon}_1$ and $\vec{\varepsilon}_2$ are the polarizations of $V_1$ and $V_2$. TP signals in the $B$ system were studied several years ago by Valencia [2], and several general studies of $B \to V_1V_2$ decays within the SM were subsequently performed [3, 4]. In Ref. [7], upon which this talk is based, these past analyses are updated and extended, and the effects of physics beyond the SM on TP asymmetries are considered.

We write the decay amplitude for $B(p) \to V_1(k_1, \varepsilon_1) + V_2(k_2, \varepsilon_2)$ as follows:

$$M = a \varepsilon_1^* \cdot \varepsilon_2^* + \frac{\hbar}{m_B^2}(p \cdot \varepsilon_1)(p \cdot \varepsilon_2^*)$$

$$+ i \frac{c}{m_B^2} \varepsilon_{\mu \nu \rho \sigma}p^\mu q^\nu \varepsilon_1^* \varepsilon_2^*$$

(4)

where $q \equiv k_1 - k_2$. (Note that we have normalized terms with a factor $m_B^2$, rather than $m_1m_2$ as in Ref. [2]. With the above normalization, each of $a$, $b$, and $c$ is expected to be the same order of magnitude.) The quantities $a$, $b$, and $c$ are complex and will in general contain both CP-conserving strong phases and CP-violating weak phases. In $|M|^2$, a triple-product correlation arises from interference terms involving the $c$ amplitude, and will be present if $\text{Im}(ac^*) = \text{Im}(bc^*)$.
is nonzero. As discussed above, true T-violating effects are obtained by comparing the triple product measured in \( B \to V_1V_2 \) with that obtained in the CP-conjugate process. In order to experimentally measure TP’s in \( B \to V_1V_2 \) decays, it is necessary to perform an angular analysis to extract the terms \( \text{Im}(ac^*) \) and \( \text{Im}(bc^*) \).

## 2 T violation in the Standard Model

To study non-leptonic \( B \) decays one starts with the SM effective hamiltonian for \( B \) decays \[ 8 \]:

\[
H^q_{	ext{eff}} = \frac{G_F}{\sqrt{2}} [V_{tb}V^*_{tq}(c_1O_1^q + c_2O_2^q) + \sum_{i=3}^{10} (V_{ub}V^*_{uq}c_i + V_{cb}V^*_{cq}c_i + V_{tb}V^*_{tq}c_i)O_i^q] + h.c., \tag{5}
\]

where the superscript \( u, c, t \) indicates the internal quark, \( f \) can be the \( u \) or \( c \) quark, and \( q \) can be either a \( d \) or \( s \) quark. Using the notation adopted in Ref. \[ 9 \], we write the operators \( O_i^q \) as

\[
\begin{align*}
O_{1,2}^q &= \bar{q}_a \gamma_\mu Lf_\beta \bar{f}_\beta \gamma_\mu Lb_\alpha \\
O_{3,5}^q &= \bar{q}_a \gamma_\mu Lb_\beta \bar{q}_\beta \gamma_\mu L(R)q' \\
O_{4,6}^q &= \bar{q}_a \gamma_\mu Lb_\beta \bar{q}_\beta \gamma_\mu L(R)q'_a \\
O_{7,9}^q &= \frac{3}{2} \bar{q}_{a\mu} Lb_\beta e_\beta \bar{q}'_\mu L(R)q' \\
O_{8,10}^q &= \frac{3}{2} \bar{q}_{a\gamma_\mu} Lb_\beta e_\beta \bar{q}'_{\gamma_\mu} L(R)q'_a,
\end{align*}
\tag{6}
\]

where \( R(L) = 1 \pm \gamma_5 \), and \( q' \) is summed over \( u, d, s, c \). \( O_2 \) and \( O_1 \) are the tree-level and QCD-corrected operators, respectively. \( O_{3-6} \) are the strong gluon-induced penguin operators, and operators \( O_{7-10} \) are due to \( \gamma \) and \( Z \) exchange (electroweak penguins), and box diagrams at loop level. The important point here is that all SM operators involve a left-handed \( b \)-quark.

Using factorization to calculate the amplitude for \( B \to V_1V_2 \), we arrive at some general conclusions for TP’s within the SM \[ 7 \]. The first observation follows from the fact that TP’s are kinematical CP-violating effects \[ 10 \]. In order to observe TP asymmetries, it is not enough just to have two decay amplitudes with a relative weak phase. What one really needs is two different kinematical amplitudes with a relative weak phase. Thus, even though there are two amplitudes with different strong and weak phases, decays like \( B \to D^* \bar{D}^* \) will not produce a TP asymmetry because the two amplitudes are not kinematically different. In fact, many SM processes have only one kinematically distinct amplitude within factorization, and so all TP asymmetries vanish for these decays.

The second point is that, even with two distinct kinematic amplitudes, TP asymmetries in the standard model are generally suppressed by flavour symmetries and by the fact that TP’s involve transverse polarization amplitudes that are mass-suppressed relative to the longitudinal polarization amplitude \[ 6 \]. (This is in contrast to \( \Lambda_b \) decays where measurable TP asymmetries may be obtained in the SM \[ 11 \].) One can avoid TP suppressions in \( B \) decays by considering excited vector mesons in the final state. Decays to radially-excited states were studied in Ref. \[ 12 \], and for some of these decays it is possible to have observable TP asymmetries in the SM \[ 6 \]. In Ref. \[ 6 \], the list of decays which exhibit TP asymmetries in the SM is presented. This list includes several modes that were not discussed in earlier work. The bottom line is that \( T \) violation in SM is tiny in most decays, and therefore any observation of a large \( T \)-violation signal would be a clear indication of new physics.

## 3 T violation with New Physics

As discussed in the previous section, most triple-product asymmetries in \( B \to V_1V_2 \) decays in the SM are predicted to be very small. The important question is then: can such TP asymmetries be large with new physics? Also, what kind of new physics can lead to large TP asymmetries?

It is fairly straightforward to see how new physics can produce a large \( T \)-violating asymmetry where the SM predicts little or no \( T \) violation. The essential point is that the effective SM Hamiltonian involves only a left-handed \( b \)-quark, and so contains only \( (V - A) \times (V - A) \) and \( (V - A) \times (V + A) \) operators. In other words it is very difficult to generate two kinematically different amplitudes in the SM. On the other hand, many models of new physics can couple to the right-handed \( b \)-quark, producing \( (V + A) \times (V - A) \) and/or \( (V + A) \times (V + A) \) operators. These new-physics operators will produce different kinematical amplitudes, leading to different phases for \( a, b \) and \( c \) \[ Eq. (4) \], thus giving rise to a TP asymmetry. Hence a large measured TP in \( B \) decays will not only be a smoking-gun signal for new physics but will also signal the presence of nonstandard operators, specifically those involving a right-handed \( b \)-quark. In fact, as was shown in Ref. \[ 13 \], by studying TP’s in several modes, one can test various models of new physics.

To demonstrate the effect of new physics in \( B \) decays, we concentrate on the decay \( B \to \phi K^* \). The
SM predicts that the indirect CP asymmetries in $B_d^0(t) \to J/\psi K_s$ and $B_d^0(t) \to \phi K_s$ are expected to be equal, both measuring $\sin 2\beta$. Any difference between these two measurements should be at most at the level of $0(\lambda^2)$, where $\lambda \sim 0.2$. However, at present this does not appear to be the case. The world averages for these measurements are $19\pm 2.0$ [14] [15].

$$\sin 2\beta \left[ J/\psi K_s \right] = 0.734 \pm 0.054,$$

$$\sin 2\beta \left[ \phi K_s \right] = -0.39 \pm 0.41.$$

(7)

Decays that have significant penguin contributions are naturally likely to be affected by physics beyond the SM [16]. As pointed out in Ref. [17], $B_d^0 \to \phi K_s$ is sensitive to new physics because it is a pure $b \to s$ penguin decay. The recent CP measurements in $B \to \phi K_s$ have led to several recent attempts to understand the data with new-physics scenarios [18, 19, 20]. (One can also look for new physics effects through the measurement of $\sin 2\beta$ in the decay $B \to \eta' K$. However, these decays have large branching ratios and other complications [21], making the search for new physics in these modes a bit problematic.)

As an example, here we focus on one particular new-physics model, that of supersymmetry with R-parity violation [19]. However, we emphasize that the analysis can be easily extended to other models of new physics. Assuming that R-parity-violating SUSY is the explanation for the CP measurements in $B_d^0(t) \to \phi K_s$, we estimate here the expected TP asymmetries in $B \to \phi K^*$ [22].

For the $b \to s s s$ transition, the relevant terms in the R-parity-violating SUSY Lagrangian are

$$L_{\text{eff}} = \frac{\lambda_{32}^2 \lambda_{22}^2}{4 m_{\tilde{q}}^2} s(1 + \gamma_5) s(1 - \gamma_5) b + \frac{\lambda_{22}^2 \lambda_{22}^4}{4 m_{\tilde{q}}^2} s(1 - \gamma_5) s(1 + \gamma_5) b .$$

(8)

(We refer to Ref. [19] for a full explanation of SUSY with R-parity violation.) The amplitude for $B \to \phi K^*$, including the new-physics contributions, can then be written as [17]

$$A[B \to \phi K^*] = \frac{G_F}{\sqrt{2}} (X + X_1) P_\phi + X_2 Q_\phi ,$$

(9)

with

$$X = - \sum_{q=u,c,t} V_{qB} V_{qs}^* \left[ (a_3^q + a_4^q + a_5^q) - \frac{1}{2} (a_9^q + a_9^q + a_{10}^q) \right] ,$$

$$X_1 = - \frac{\sqrt{2} \lambda_{32}^2 \lambda_{22}^2}{G_F 24 m_{\tilde{q}}^2} s(1 + \gamma_5) s(1 - \gamma_5) b ,$$

$$X_2 = - \frac{\sqrt{2} \lambda_{22}^2 \lambda_{22}^4}{G_F 24 m_{\tilde{q}}^2} s(1 - \gamma_5) s(1 + \gamma_5) b .$$

(10)

For $B_d^0 \to \phi K_s$, it is the combination $X_1 + X_2$ which contributes [19], and we can define the quantity $X_R$ via

$$X_1 + X_2 = \frac{\sqrt{2} X_R}{G_F 12 M_{\phi}^2} \phi ,$$

(11)

where $\phi$ is the weak phase in the R-parity-violating couplings, and $M$ is a mass scale with $M \sim m_{\tilde{q}}$. In order to reproduce the CP-violating $B_d^0(t) \to \phi K_s$ measurement in Eq. (7), one requires $|X_R| \sim 1.5 \times 10^{-3}$ for $M = 100$ GeV, along with a value for the phase $\phi$ near $\pi/2$. In our calculations of TP’s in $B \to \phi K^*$ we make the simplifying assumption that $X_1 = X_2$, and choose $\phi = \pi/2$.

We present our results in Table. [1] These results hold for both neutral and charged $B$ decays. The predicted branching ratio for $B \to \phi K^*$ is slightly larger than the measured branching ratios $BR(B^+ \to \phi K^{+*}) = 10_{-5}^{+4} \times 10^{-6}$ and $BR(B_d^0 \to \phi K^{*0}) = 9.5_{-2.0}^{+2.4} \times 10^{-6}$ [23], but it is well within the theoretical uncertainties of the calculation. The important result is that we expect very large (15–20%) TP asymmetries for these decays, as well as for those with radially-excited final states.

As emphasized above, these large TP asymmetries are not unique to supersymmetry with R-parity violation. One expects to find large TP asymmetries in many other models of physics beyond the SM. The measurement of such TP asymmetries would not only reveal the presence of new physics, but more specifically it would point to new physics which includes large couplings to the right-handed $b$-quark.

| Process | BR | $A_T^{(1)} \%$ |
|---------|----|----------------|
| $B \to \phi K^*$ | $16.7 (17.4) \times 10^{-6}$ | $-16.3 (-15.6)$ |
| $B \to \phi' K^*$ | $19.1 (20.7) \times 10^{-6}$ | $-21.0 (-19.3)$ |
| $B \to \phi K^{*0}$ | $28.0 (28.9) \times 10^{-6}$ | $-15.4 (-14.8)$ |

Table 1. Branching ratios (BR) and triple-product asymmetries ($A_T^{(1)}$) for $B \to \phi K^*$ and excited states, for $N_c = 3$ (pure factorization). The results for the CP-conjugate process are given in parentheses.
4 Summary

In summary, we have examined T violation in B decays to two vector mesons. We find that T-violating effects in the SM are tiny, except for a few cases with radially-excited vector mesons in the final state. On the other hand T violation with physics beyond the SM can be large and measurable. T-violating asymmetries are therefore excellent probes of the presence and nature of new physics.

References

1. For a review, see, for example, The BaBar Physics Book, eds. P.F. Harrison and H.R. Quinn, SLAC Report 504, October 1998.
2. G. Valencia, Phys. Rev. D39, 3339 (1989).
3. G. Kramer and W.F. Palmer, Phys. Rev. D45, 193 (1992), Phys. Lett. 279B, 181 (1992), Phys. Rev. D46, 2969 (1992); G. Kramer, W.F. Palmer and T. Mannel, Zeit. Phys. C55, 497 (1992); G. Kramer, W.F. Palmer and H. Simma, Nucl. Phys. B428, 77 (1994); A.N. Kamal and C.W. Luo, Phys. Lett. 388B, 633 (1996).
4. A.S. Dighe, I. Dunietz, H.J. Lipkin and J.L. Rosner, Phys. Lett. 369B, 144 (1996); B. Tseng and C.-W. Chiang, hep-ph/9905338.
5. N. Sinha and R. Sinha, Phys. Rev. Lett. 80, 3706 (1998); C.-W. Chiang and L. Wolfenstein, Phys. Rev. D61, 074301 (2000).
6. The full time-dependent \( B \to V_1 V_2 \) angular distribution is discussed in C.-W. Chiang, Phys. Rev. D62, 014017 (2000).
7. A. Datta and D. London, arXiv:hep-ph/0303159.
8. See, for example, G. Buchalla, A.J. Buras and M.E. Lautenbacher, Rev. Mod. Phys. 68, 1125 (1996), A.J. Buras, “Weak Hamiltonian, CP Violation and Rare Decays,” in Probing the Standard Model of Particle Interactions, ed. F. David and R. Gupta (Elsevier Science B.V., 1998), pp. 281-539.
9. T. E. Browder, A. Datta, X. G. He and S. Pakvasa, Phys. Rev. D 57, 6829 (1998) arXiv:hep-ph/9705320.
10. B. Kayser, Nucl. Phys. Proc. Suppl. 13, 487 (1990).
11. W. Bensalem, A. Datta and D. London, Phys. Lett. B 538, 309 (2002).
12. A. Datta, H.J. Lipkin and P.J. O’Donnell, Phys. Lett. B 529, 93 (2002).
13. W. Bensalem, A. Datta and D. London, Phys. Rev. D 66, 094004 (2002).
14. \( B^0_d \to J/\psi K_S \): B. Aubert et al. (BABAR Collaboration), hep-ex/0207042
15. \( B^0_d \to dK_S \): B. Aubert et al. (BABAR Collaboration), hep-ex/0207070
16. See, for example, G. Buchalla, A.J. Buras and J. Rosner, Phys. Rev. D 45, 2746 (1992); M. Ciuchini and L. Silvestrini, Phys. Rev. Lett. 89, 231802 (2002); M. Raidal, Phys. Rev. Lett. 89, 231803 (2002); J.P. Lee and K.Y. Lee, arXiv:hep-ph/0209290.
17. W. Bensalem, A. Datta and D. London, arXiv:hep-ph/0302123.
18. S. Khalil and E. Kou, arXiv:hep-ph/0212023.
19. A. Datta, Phys. Rev. D 66, 071702 (2002).
20. B. Dutta, C.S. Kim and S. Oh, Phys. Rev. Lett. 90, 011801 (2003); A. Kundu and T. Mitra, arXiv:hep-ph/0302123.
21. See, for example, A. Datta, H.J. Lipkin and P.J. O’Donnell, Phys. Lett. B 540, 97 (2002), Phys. Lett. B 544, 145 (2002).
22. In the same spirit, for a comparison of \( B^0_d \to J/\psi K_S \) and \( B \to J/\psi K^* \), see D. London, N. Sinha and R. Sinha, arXiv:hep-ph/0207007.
23. D.E. Groom et al. (Particle Data Group), Eur. Phys. J. C15 (2000) 1.