Opposite-sign Dilepton Asymmetry of Neutral $B$ Decays: a Probe of New Physics from $CPT$ or $\Delta B = \Delta Q$ Violation

Zhi-zhong Xing

Sektion Physik, Universität München, Theresienstrasse 37A, 80333 München, Germany

Abstract

We show that new physics, either from $CPT$ violation in $B^0$-$\bar{B}^0$ mixing or from $\Delta B = -\Delta Q$ transitions, may lead to an opposite-sign dilepton asymmetry of neutral $B$-meson decays. Both effects have the same time-dependent behavior and therefore are in general indistinguishable from each other. We also clarify some ambiguity associated with the constraint on $CPT$ violation in semileptonic decays of incoherent $B^0$ and $\bar{B}^0$ mesons.

1 E-mail: Xing@hep.physik.uni-muenchen.de
The $B$-meson factories under construction are going to provide a unique opportunity for the study of $CP$ violation, both its phenomenon and its origin. At the second or final stage of these facilities sufficient $B\bar{B}$ events (e.g., $N_{BB} \geq 10^9$) will be accumulated, then a direct test of the $CPT$ symmetry and the $\Delta B = \Delta Q$ rule should be experimentally feasible. This is expected to open a new window for probing new physics beyond the standard model, as both $CPT$ and $\Delta B = \Delta Q$ conservation laws work extremely well within the standard model. Up to now some phenomenological analyses of possible $CPT$-violating signals in semileptonic and nonleptonic decays of neutral $B$ mesons have been made in Refs. [1] – [6], whose results depend on the validity of the $\Delta B = \Delta Q$ rule. The possibility to detect the effect of $\Delta B = -\Delta Q$ transitions at $B$ factories has been investigated in Ref. [7] in the assumption of $CPT$ invariance.

It was noticed in Refs. [1] – [6] that $CPT$ violation in $B^0-\bar{B}^0$ mixing could lead to an opposite-sign dilepton asymmetry of neutral-$B$ decays, or more generally, an asymmetry between $B^0(t) \rightarrow B^0 \rightarrow l^+X^-$ and $\bar{B}^0(t) \rightarrow \bar{B}^0 \rightarrow l^-X^+$ decay rates. Applying this idea to the time-dependent semileptonic decays of $B^0$ and $\bar{B}^0$ mesons at the $Z$ resonance, the OPAL Collaboration obtained a constraint on the $CPT$-violating parameter $\delta_B$, i.e., $\text{Im}\delta_B = -0.020 \pm 0.016 \pm 0.006$ [3]. The ideal experimental environment for measuring the time distribution of opposite-sign dilepton events will be at the KEK and SLAC asymmetric $B$-meson factories, where $B^0\bar{B}^0$ pairs can coherently be produced through the decay of the $\Upsilon(4S)$ resonance.

Allowing both $CPT$ violation and $\Delta B = -\Delta Q$ transitions, we shall carry out a new analysis of the opposite-sign dilepton asymmetry of neutral $B$ decays and clarify some ambiguity associated with the constraint on $CPT$ violation in semileptonic decays of incoherent $B^0$ and $\bar{B}^0$ mesons. It is shown that the effect of $\Delta B = -\Delta Q$ transitions and that of $CPT$ violation have the same time-dependent behavior in the opposite-sign dilepton events, therefore they are in general indistinguishable from each other. We point out that a meaningful constraint on $\text{Im}\delta_B$ depends actually on the smallness of the decay width difference between two neutral-$B$ mass eigenstates, on the condition $|\text{Re}\delta_B| \leq |\text{Im}\delta_B|$, and on the validity of the $\Delta B = \Delta Q$ rule.

Mixing between $B^0$ and $\bar{B}^0$ mesons arises naturally from their common coupling to a subset of real and virtual intermediate states, hence the mass eigenstates $|B_1\rangle$ and $|B_2\rangle$ are different from the flavor eigenstates $|B^0\rangle$ and $|\bar{B}^0\rangle$. A non-linear parametrization of $CPT$- and $CPT$-violating effects in $B^0-\bar{B}^0$ mixing reads as

$$
|B_1\rangle = \cos \frac{\theta}{2} e^{-i\frac{\phi}{2}} |B^0\rangle + \sin \frac{\theta}{2} e^{+i\frac{\phi}{2}} |\bar{B}^0\rangle,
$$

$$
|B_2\rangle = \sin \frac{\theta}{2} e^{-i\frac{\phi}{2}} |B^0\rangle - \cos \frac{\theta}{2} e^{+i\frac{\phi}{2}} |\bar{B}^0\rangle,
$$

where $\theta$ and $\phi$ are in general complex, and the normalization factors of $|B_1\rangle$ and $|B_2\rangle$ have
been neglected. CPT invariance requires $\cos \theta = 0$, while CP conservation requires both $\cos \theta = 0$ and $\phi = 0$ \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}. In some literature the linear parametrization \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}

\begin{align*}
|B_1\rangle & = (1 + \epsilon_B + \delta_B)|B^0\rangle + (1 - \epsilon_B - \delta_B)|\bar{B}^0\rangle , \\
|B_2\rangle & = (1 + \epsilon_B - \delta_B)|B^0\rangle - (1 - \epsilon_B + \delta_B)|\bar{B}^0\rangle ,
\end{align*}

(2)
together with the conventions $|\epsilon_B| \ll 1$ and $|\delta_B| \ll 1$, has been adopted (here again the normalization factors of $|B_1\rangle$ and $|B_2\rangle$ are neglected). It is straightforward to find the relationship between $(\theta, \phi)$ and $(\delta_B, \epsilon_B)$ parameters in the leading-order approximation, $\epsilon_B \approx i\phi/2$ and $\delta_B \approx \cot \theta/2$, provided the conventions $|\cos \theta| \ll 1$ and $|\phi| \ll 1$ are taken. Note that the requirement $|\epsilon_B| \ll 1$ (or $|\phi| \ll 1$) corresponds to an exotic phase convention of quark fields, which is incompatible with several popular parametrizations of the quark flavor mixing matrix \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}. In subsequent calculations we shall mainly make use of the $(\theta, \phi)$ notation (in which $\phi$ may take arbitrary values), and translate it into the $(\delta_B, \epsilon_B)$ notation when necessary.

The proper-time evolution of an initially pure $|B^0\rangle$ or $|\bar{B}^0\rangle$ state is then given as \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}

\begin{align*}
|B^0(t)\rangle & = e^{-\left(\text{i}m + \frac{\text{i}y}{2}\right)t} \left|g_+(t)|B^0\rangle + \tilde{g}_+(t)|\bar{B}^0\rangle\right| , \\
|\bar{B}^0(t)\rangle & = e^{-\left(\text{i}m + \frac{\text{i}y}{2}\right)t} \left|g_-(t)|\bar{B}^0\rangle + \tilde{g}_-(t)|B^0\rangle\right| ,
\end{align*}

(3)
where

\begin{align*}
g_{\pm}(t) & = \cosh \left(\frac{\text{i}x - y}{2}\Gamma t\right) \pm \cos \theta \sinh \left(\frac{\text{i}x - y}{2}\Gamma t\right) , \\
\tilde{g}_{\pm}(t) & = \sin \theta \ e^{\pm \phi} \sinh \left(\frac{\text{i}x - y}{2}\Gamma t\right) .
\end{align*}

(4)
In Eqs. (3) and (4) we have defined $m \equiv (m_1 + m_2)/2$, $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$, $x \equiv (m_2 - m_1)/\Gamma$ and $y \equiv (\Gamma_1 - \Gamma_2)/(2\Gamma)$, where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and width of $B_{1,2}$. The mixing parameter $x \approx 0.7$ has been measured \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}, and $y \sim O(10^{-2})$ is theoretically expected \footnote{Here we use the notation $(\delta_B, \epsilon_B)$ instead of $(\delta, \epsilon)$, as the latter is commonly adopted to describe CPT- and CP-violating effects in the $K^0\bar{K}^0$ mixing system.}. To calculate the time distribution of opposite-sign dilepton events on the $\Upsilon(4S)$ resonance, we neglect possible tiny effects from electromagnetic final-state interactions and assume CPT invariance in the direct transition amplitudes of semileptonic $B$ decays. Such an assumption can be examined, without the mixing-induced complexity, by measuring the charge asymmetry of semileptonic $B^\pm$ decays. The effect of possible $\Delta B = -\Delta Q$ transitions need be taken into account. We then write the relevant semileptonic decay amplitudes as follows:

\begin{align*}
\langle l^+|B^0\rangle & = A_l , \\
\langle l^+|\bar{B}^0\rangle & = \sigma_l A_l ; \\
\langle l^-|\bar{B}^0\rangle & = A_l^* , \\
\langle l^-|B^0\rangle & = \sigma_l^* A_l^* ,
\end{align*}

(5)
where $\sigma_t$ measures the $\Delta B = -\Delta Q$ effect and $|\sigma_t| \ll 1$ holds.

$|\sigma_t| \neq 0$ implies that it is in practice impossible to have a pure tagging of the $B^0$ or $\bar{B}^0$ state through its semileptonic decay (to $l^+$ or $l^-$). For $B^0\bar{B}^0$ pairs produced incoherently on the $Z$ resonance or elsewhere, the assumption $|\sigma_t| = 0$ (i.e., the exact $\Delta B = \Delta Q$ rule) is indeed a necessary condition to get pure flavor tagging of $B^0$ and $\bar{B}^0$ mesons and to study possible tiny violation of $CPT$ symmetry in their semileptonic decays.

The pure flavor tagging is however unnecessary for the study of fine effects induced by $CPT$ violation and (or) $\Delta Q$ transitions in opposite-sign dilepton products of coherent $B^0\bar{B}^0$ pairs on the $\Upsilon(4S)$ resonance. Here the decay of one neutral $B$ meson at proper time $t_1$ into a semileptonic state (e.g., $e^\pm X^\mp_e$) may only serve as a rough flavor tagging for the other meson decaying at proper time $t_2$ into another semileptonic state (e.g., $\mu^\pm X^\mp_\mu$). The overall final state is therefore an opposite-sign dilepton event. Since we are only interested in how the decay rate depends on the time difference $t_2 - t_1$ at an asymmetric $B$ factory, we just take $t_1 = 0$ and $t_2 = t$ with the convention $t > 0$ for the wave function of the coherent $B^0\bar{B}^0$ pair:

$$\Psi(t) = \frac{1}{\sqrt{2}} \left[ |B^0(0)\rangle \otimes |\bar{B}^0(t)\rangle - |B^0(t)\rangle \otimes |\bar{B}^0(0)\rangle \right].$$

Then the rates of two opposite-sign dilepton decays (with $l^\pm$ events at $t = 0$) read

$$\mathcal{R}(t) \equiv |\langle l^+l^-|\Psi(t)\rangle|^2 = \frac{1}{2} |A_l|^2 |A_{l'}|^2 e^{-\Gamma t} \left| g_-(t) + \tilde{g}_-(t) \sigma_t - \tilde{g}_+(t) \sigma_t \right|^2,$$

$$\tilde{\mathcal{R}}(t) \equiv |\langle l^-l'^+|\Psi(t)\rangle|^2 = \frac{1}{2} |A_l|^2 |A_{l'}|^2 e^{-\Gamma t} \left| g_+(t) + \tilde{g}_+(t) \sigma_t - \tilde{g}_-(t) \sigma_t \right|^2,$$

where only the contributions of $O(|\sigma_t|)$ and $O(|\sigma_{l'}|)$ are kept, and the functions $g_{\pm}(t)$ and $\tilde{g}_{\pm}(t)$ can be found in Eq. (3). We arrive finally at

$$\mathcal{R}(t) = \frac{1}{4} |A_l|^2 |A_{l'}|^2 e^{-\Gamma t} \left[ \cosh(y \Gamma t) + 2 \text{Re} \Omega \sinh(y \Gamma t) \right.$$

$$+ \cos(x \Gamma t) + 2 \text{Im} \Omega \sin(x \Gamma t) \left. \right],$$

$$\tilde{\mathcal{R}}(t) = \frac{1}{4} |A_l|^2 |A_{l'}|^2 e^{-\Gamma t} \left[ \cosh(y \Gamma t) - 2 \text{Re} \bar{\Omega} \sinh(y \Gamma t) \right.$$

$$+ \cos(x \Gamma t) - 2 \text{Im} \bar{\Omega} \sin(x \Gamma t) \left. \right],$$

where

$$\Omega = \cos \theta + \xi_{l'} \sin \theta,$$

$$\bar{\Omega} = \cos \theta + \bar{\xi}_{l'} \sin \theta,$$

Note that the treatment in Ref. [3], which takes $|\sigma_t| \neq 0$ on the one hand but assumes the pure flavor tagging of $B^0$ and $\bar{B}^0$ states on the other hand, is controversial in the experimental environment where $B^0\bar{B}^0$ pairs are incoherently produced.
and
\[
\xi_{l'} = \sigma_l e^{+i\phi} - \sigma^*_l e^{-i\phi}, \\
\bar{\xi}_{l'} = \sigma_{l'} e^{+i\phi} - \sigma^*_{l'} e^{-i\phi}.
\]

(10)

In obtaining Eq. (8) we have neglected the contributions of \(O(|\Omega|^2)\) and \(O(|\bar{\Omega}|^2)\).

Obviously the \(\Delta B = -\Delta Q\) effects are signified by the rephasing-invariant parameters \(\xi_{l'}\) and \(\bar{\xi}_{l'}\). \(\xi_{l'} = \bar{\xi}_{l'}\) holds for \(l' = l\), and \(\xi_{l'} = -\bar{\xi}_{l'}\) holds if \(\text{Im}\phi = 0\). We find that \(\xi_{l'}\) or \(\bar{\xi}_{l'}\) has the same time-dependent behavior as the \(CPT\)-violating parameter \(\cos\theta\) in the decay rate \(\mathcal{R}(t)\) or \(\bar{\mathcal{R}}(t)\). This important feature implies that it is in general impossible to distinguish between the effects of \(CPT\) violation and \(\Delta B = -\Delta Q\) transitions in the opposite-sign dilepton events, unless one of them is remarkably smaller than the other.

For illustration we simplify the result in Eq. (8) by taking \(\sigma_l = \sigma_{l'} = 0\), i.e, no \(\Delta B = -\Delta Q\) transition involved. In this case one gets
\[
\begin{align*}
\text{Re}(\Omega + \bar{\Omega}) &= 2\text{Re}(\cos\theta), \\
\text{Im}(\Omega + \bar{\Omega}) &= 2\text{Im}(\cos\theta),
\end{align*}
\]
which results in an asymmetry between the decay rates \(\mathcal{R}(t)\) and \(\bar{\mathcal{R}}(t)\). Defining \(A(t)\) as the ratio of \(\mathcal{R}(t) - \bar{\mathcal{R}}(t)\) to \(\mathcal{R}(t) + \bar{\mathcal{R}}(t)\), we then have
\[
A(t) = 2 \frac{\text{Re}(\cos\theta) \sinh(y\Gamma t) + \text{Im}(\cos\theta) \sin(x\Gamma t)}{\cosh(y\Gamma t) + \cos(x\Gamma t)},
\]

(12)

which is independent of the \(CPT\)-violating parameter \(\phi\). This formula has already been obtained in Refs. [4] and [6]. It should be noted that the asymmetry \(A(t)\), due to its time dependence, is not restricted to the range \([-1, +1]\). In the limit \(y = 0\), Eq. (12) turns out to be \(A(t) = 2\text{Im}(\cos\theta) \tan(x\Gamma t/2)\), which becomes infinity on the point \(\Gamma t = \pi/x\) (i.e., around \(\Gamma t \approx 4.5\)).

If one translates \(\cos\theta\) into \(\delta_B\), then \(\text{Re}(\cos\theta) \approx 2\text{Re}\delta_B\) and \(\text{Im}(\cos\theta) \approx 2\text{Im}\delta_B\). Therefore a constraint on \(\text{Im}\delta_B\) is achievable from Eq. (12) with \(y = 0\). This is indeed the case taken by the OPAL Collaboration in their measurement [8], where the rate difference between \(B^0(t) \to B^0 \to l^+X^-\) and \(\bar{B}^0(t) \to \bar{B}^0 \to l^-X^+\) transitions is essentially equivalent to the asymmetry of opposite-sign dilepton events of \(B^0\bar{B}^0\) decays under discussion. As the theoretical calculation favors \(y/x \sim 10^{-2}\) [12], the approximation \(y \approx 0\) made in Ref. [8] seems quite reasonable.

However, such an approximation may not be valid if \(|\text{Re}\delta_B| \gg |\text{Im}\delta_B|\) holds. Although there is no experimental information about the relative magnitude of \(\text{Re}\delta_B\) and \(\text{Im}\delta_B\), a

\[\text{Note that the definitions of } y \text{ in Refs. [4] and [6] are different in sign. Taking this into account, one can get full consistency between the results in these two papers.}\]
string theory with spontaneous $CPT$ violation and Lorentz symmetry breaking predicts $[3]
\[ r \equiv \frac{\text{Re} \delta_B}{\text{Im} \delta_B} = \pm \frac{x}{y} \sim \pm 10^2. \] (13)
In this case, the $\sinh(y \Gamma t)$ and $\sin(x \Gamma t)$ terms in the numerator of $A(t)$ are comparable in magnitude even for small $t$. Then a meaningful constraint on $\text{Im} \delta_B$ becomes impossible. To illustrate, we plot the time distribution of $A(t)$ in Fig. 1 with the inputs $r = \pm 1$ and $r = \pm 100$ (for fixed $\text{Im} \delta_B$), respectively. It is obvious in the latter case that the $\text{Re} \delta_B$ contribution to $A(t)$ is significant (even dominant for large $\Gamma t$) and a separate bound on $\text{Im} \delta_B$ cannot be obtained.

Next let us simplify the result in Eq. (8) by taking $\cos \theta = 0$ or $\sin \theta = 1$, i.e., no $CPT$ violation in $B^0 - \bar{B}^0$ mixing involved. In this case we obtain
\[ \text{Re}(\Omega + \bar{\Omega}) = 2 \sinh(\text{Im}\phi) [\text{Im}Z' \sin(\text{Re}\phi) - \text{Re}Z' \cos(\text{Re}\phi)] , \]
\[ \text{Im}(\Omega + \bar{\Omega}) = 2 \cosh(\text{Im}\phi) [\text{Im}Z' \cos(\text{Re}\phi) + \text{Re}Z' \sin(\text{Re}\phi)] , \] (14)
where $Z' \equiv \sigma_l + \sigma_{l'}$ with $|Z'| \ll 1$. Note that $\text{Im}\phi$ describes the $CP$-violating effect induced by $B^0 - \bar{B}^0$ mixing and can in principle be measured (or constrained) from the same-sign dilepton asymmetry of neutral-$B$ decays (see, e.g., Refs. [1, 4]). The magnitude of $\text{Im}\phi$ is expected to be of $O(10^{-3})$ within the standard model, but it might be enhanced to $O(10^{-2})$ if there exists the $CP$-violating new physics in $B^0 - \bar{B}^0$ mixing [13]. Anyway the $\text{Re}(\Omega + \bar{\Omega})$ term is doubly suppressed by $\text{Im}\phi$ and $|Z'|$, therefore it can be neglected in the rate difference between $\mathcal{R}(t)$ and $\bar{\mathcal{R}}(t)$. The asymmetry $A'(t)$, defined as the ratio of $\mathcal{R}(t) - \bar{\mathcal{R}}(t)$ to $\mathcal{R}(t) + \bar{\mathcal{R}}(t)$, is then governed by the $\text{Im}(\Omega + \bar{\Omega})$ term with $\cosh(\text{Im}\phi) \approx 1$ as follows:
\[ A'(t) = 2 \frac{[\text{Im}Z' \cos(\text{Re}\phi) + \text{Re}Z' \sin(\text{Re}\phi)] \sin(x \Gamma t)}{\cosh(y \Gamma t) + \cos(x \Gamma t)}. \] (15)
This instructive result implies that a signal of $\Delta B = -\Delta Q$ transitions can emerge from the opposite-sign dilepton asymmetry of neutral-$B$ decays, if $CPT$ violation is absent or negligibly small. Whether the effect of $\Delta B = \Delta Q$ violation is significant or not beyond the standard model, however, remains an open question.

Comparing Eq. (15) with Eq. (12), one can see that the neglect of the $\sinh(y \Gamma t)$ term in $A'(t)$ is much safer than that in $A(t)$. In general, the $\text{Re}(\Omega + \bar{\Omega})$ and $\text{Im}(\Omega + \bar{\Omega})$ terms may consist of comparable effects from $CPT$ violation and $\Delta B = -\Delta Q$ transitions. Hence a constraint on $\text{Im}(\cos \theta)$ or $\text{Im} \delta_B$, due to the presence of $\Delta B = -\Delta Q$ contamination, becomes impossible in the opposite-sign dilepton events.

Keeping with the current experimental interest in tests of discrete symmetries and conservation laws at the upcoming $B$ factories, we have made a new analysis of the opposite-sign
dilepton decays of neutral-$B$ mesons. It is shown that the effects of $\Delta B = -\Delta Q$ transitions and $CPT$ violation have the same time-dependent behavior in such dilepton events, hence they are in general indistinguishable from each other. To separate one kind of new physics from the other will require some delicate measurements of the opposite-sign dilepton events, the same-sign dilepton events, and other relevant nonleptonic decay channels. We remark that an experimental bound on the $CPT$-violating parameter $\text{Im}\delta_B$ relies on the assumptions $y \approx 0$ and $|\text{Re}\delta_B| \leq |\text{Im}\delta_B|$ as well as the validity of the $\Delta B = \Delta Q$ rule. For this reason the value obtained in Ref. [8] can only shed limited light on $CPT$ invariance or its possible violation in the $B^0 - \bar{B}^0$ mixing system. However, a new analysis of the old data is likely to give a constraint on the imaginary part of $(\Omega + \bar{\Omega})$, provided its real part is not significant.

We hope that a useful test of $CPT$ and $\Delta B = \Delta Q$ conservation laws can finally be realized at the asymmetric $B$-meson factories. The prospect of such ambitious experiments, as discussed in Ref. [6], is not dim. And the relevant theoretical motivation seems encouraging too [14]. On the phenomenological side, further and more general analyses of $CP$-violating, $CPT$-violating and $\Delta B = -\Delta Q$ effects on all types of neutral $B$-meson decays are therefore desirable.

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Figure 1: Illustrative plot for the time distribution of $A(t)$ with $r \equiv \text{Re} \delta_B/\text{Im} \delta_B = \pm 1$ or $\pm 100$, where $x = 0.7$ and $y = 0.01$ have typically been taken.