LEPTON CP ASYMMETRY IN B FACTORIES: 
\( \epsilon_B \) AND NEW PHYSICS

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In this talk, we first make some brief comments on the phase-convention dependence of the CP-violating parameter \( \epsilon_B \). A simple framework is then presented for analyzing new physics contributions to \( B^0-\bar{B}^0 \) mixing and their effects on the lepton CP asymmetry, a promising signal to be further searched for in the first-round experiments of \( B \) factories.

1 Introduction

The study of various possible CP-violating phenomena in weak \( B \)-meson decays, starting from the end of 1970’s, becomes more intensive today – on the eve of KEK and SLAC \( B \) factories, which will provide a unique opportunity to test the Kobayashi-Maskawa (KM) mechanism of CP violation in the standard model (SM) and to discover possible new physics (NP) beyond the SM.

Phenomenologically three different types of CP-violating signals are expected in neutral \( B \)-meson transitions: (a) CP violation from \( B^0-\bar{B}^0 \) mixing; (b) CP violation from direct \( b \)-quark decay; and (c) CP violation from the interplay of decay and mixing. Type (a) can be detected most appropriately from the decay-rate asymmetry between two semileptonic channels \( B^0 \rightarrow l^+\nu_l X^- \) and \( \bar{B}^0 \rightarrow l^-\bar{\nu}_l X^+ \), the so-called “lepton CP asymmetry” (denoted as \( A_{SL} \) below). Type (b) may involve large uncertainties associated with the evaluation of hadronic matrix elements and (or) penguin contributions. Type (c) should play a crucial role in determining the KM CP-violating phase and (or) the NP phase(s), as it is independent of hadron or penguin pollution to a good degree of accuracy in some decay modes.

Experimentally, however, only the lepton CP asymmetry \( A_{SL} \) has been searched for to date. An upper bound on this asymmetry was first set by the CLEO time-integrated measurement: \(|A_{SL}| < 0.18\) or \(\text{Re}\epsilon_B < 0.045\) at the 90% confidence level where \( \epsilon_B \) is a CP-violating parameter of \( B^0-\bar{B}^0 \) mixing defined like \( \epsilon_K \) in the neutral kaon system. The OPAL time-dependent measurement has recently given a more accurate result: \(\text{Re}\epsilon_B = 0.002 \pm 0.007 \pm 0.003\) in a special convention used for \( \epsilon_B \), which is equivalent to \( A_{SL} = 0.008 \pm 0.028 \pm 0.012 \). Both experiments are consistent with the standard model prediction, i.e., \(|A_{SL}| \sim 10^{-3}\) or smaller. It should be noted, nevertheless, the existence of NP in \( B^0-\bar{B}^0 \) mixing is possible to enhance \( A_{SL} \) up to the percent level, observable in the first-round experiments of a \( B \)-meson factory with
about \(10^8\) events of \(B^0 \bar{B}^0\) mesons.

The purposes of this talk are: (1) to comment on the phase convention dependence of the parameter \(\epsilon_B\); and (2) to present a simple framework for analyzing NP effect on \(A_{SL}\). We expect that the further measurement of \(A_{SL}\) and its correlation with other \(CP\) asymmetries may serve as a sensitive probe for NP in \(B^0-\bar{B}^0\) mixing.

2 Comments on \(\epsilon_B\)

In some literature, the \(CP\)-violating parameter \(\epsilon_B\) is defined to relate the flavor eigenstates |\(B^0\rangle\) and |\(\bar{B}^0\rangle\) to the mass eigenstates |\(B_1\rangle\) and |\(B_2\rangle\):

\[
|B_{1,2}\rangle = \frac{1}{\sqrt{2(1 + |\epsilon_B|^2)}} \left[ (1 + \epsilon_B) |B^0\rangle \pm (1 - \epsilon_B) |\bar{B}^0\rangle \right].
\]  

Certainly \(\epsilon_B\) has the phase freedom arising from the bound states |\(B^0\rangle\) and |\(\bar{B}^0\rangle\). The reason is simply that |\(B^0\rangle\) and |\(\bar{B}^0\rangle\) are defined by strong interactions only, leaving the relative phase between them undetermined. The dependence of \(\epsilon_B\) on the bound-state phase convention can be removed, if one adopts the definition to link the \(CP\) eigenstates |\(B^+\rangle\) (\(CP\)-even) and |\(B^-\rangle\) (\(CP\)-odd) with the mass eigenstates |\(B_1\rangle\) and |\(B_2\rangle\):

\[
|B_{1,2}\rangle = \frac{1}{\sqrt{1 + |\epsilon_B|^2}} \left[ |B^\pm\rangle + \epsilon_B |B^\mp\rangle \right].
\]  

Note that \(\epsilon_B\) and \(\epsilon_B\) are not identical, unless we fix the \(CP\) transformation between |\(B^0\rangle\) and |\(\bar{B}^0\rangle\) as \((CP)|B^0\rangle = \pm |\bar{B}^0\rangle\). Therefore it is better to adopt the phase-convention independent parameter \(\epsilon_B\), other than \(\epsilon_B\), in phenomenological applications. In the analyses of CLEO and OPAL measurements, however, the phase-convention dependent parameter \(\epsilon_B\) has been used.

The more important point is that both \(\epsilon_B\) and \(\epsilon_B\) depend on the phase convention of the KM matrix for quark flavor mixings, although \(\epsilon_B\) itself is independent of the bound-state phases of |\(B^0\rangle\) and |\(\bar{B}^0\rangle\). The KM phase convention comes from the freedom in defining the quark field phases, thus different parametrizations of the KM matrix may result in different values for \(\epsilon_B\) and \(\epsilon_B\). In this sense, even \(\epsilon_B\) is not a physically well-defined parameter.

In the CLEO and OPAL analyses, \(\text{Im} \epsilon_B = 0\) or \(\text{Im} \epsilon_B \ll 1\) has been assumed in an undemonstrative way. That is why these analyses can yield an upper bound on Re\(\epsilon_B\) solely from the measurement of the lepton \(CP\) asymmetry. To see this point more clearly, let us take the CLEO constraint on Re\(\epsilon_B\) into account. The dilepton \(CP\) asymmetry measured on the \(\Upsilon(4S)\)
resonance reads

\[ A_{SL}(\varepsilon) = \frac{4 \text{Re} \varepsilon (1 + |\varepsilon|^2)}{(1 + |\varepsilon|^2)^2 + 4(\text{Re} \varepsilon)^2}, \]  

and \( A_{SL}(\varepsilon) = A_{SL}(\varepsilon) \) holds. Only in the assumption \( |\text{Im} \varepsilon| \ll 1 \) (and \( |\text{Re} \varepsilon| \ll 1 \)), one can get \( A_{SL}(\varepsilon) \approx 2 \text{Re} \varepsilon \). Then \( |A_{SL}(\varepsilon)| < 0.18 \) leads to \( |\text{Re} \varepsilon| < 0.045 \). If one takes \( |\text{Im} \varepsilon| \sim 1 \), however, \( A_{SL}(\varepsilon) \approx 2 \text{Re} \varepsilon \) appears and a different upper bound on \( \text{Re} \varepsilon \) must turn out from the same measurement of \( A_{SL}(\varepsilon) \). Indeed the condition \( \text{Im} \varepsilon = 0 \) corresponds to a special parametrization of the KM matrix which has \( \text{Im} V_{td} = \text{Im} V_{tb} = 0 \) (e.g., the one proposed recently by Fritzsch and the author). In contrast, the condition \( |\text{Im} \varepsilon| \approx \mathcal{O}(1) \) may be satisfied in the “standard” parametrization or the Wolfenstein form.

3 NP effect on \( A_{SL} \)

Now we present a simple framework to analyze NP contributions to \( A_{SL} \) and other CP asymmetries via \( B^0 - \bar{B}^0 \) mixing. In terms of the off-diagonal elements of the \( 2 \times 2 \) \( B^0 - \bar{B}^0 \) mixing Hamiltonian \( \mathbf{M} - i \Gamma/2 \), \( A_{SL} \) can be written as

\[ A_{SL} = \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right). \]  

In most extensions of the SM, NP can significantly contribute to \( M_{12} \). However, NP is not expected to significantly affect the direct \( B \)-meson decays via the tree-level \( W \)-mediated channels. Thus \( \Gamma_{12} = \Gamma_{12}^{SM} \) holds as a good approximation, where

\[ \Gamma_{12}^{SM} = -\frac{G_F^2 \mathcal{B} \mathcal{F} \mathcal{B} M_B m_b^2}{8\pi} \left[ (\xi_u^*)^2 T_u + (\xi_c^*)^2 T_c + (\xi_t^*)^2 T_t \right]. \]  

with KM factors \( \xi_i \equiv V_{ib}^* V_{id} \) \((i = u, c, t)\) for three quark families and QCD correction factors \( T_u \sim -T_c \sim 0.1 \) and \( T_t \sim 1 \). In the presence of NP, \( M_{12} \) can be written as

\[ M_{12} = M_{12}^{SM} + M_{12}^{NP}. \]  

Rescaling three complex quantities in Eq. (6) by \( |M_{12}| = \Delta M/2 \), where \( \Delta M = (0.464 \pm 0.018) \text{ ps}^{-1} \) has been measured, we obtain a parametrized triangle in the complex plane (see Fig. 1). The correlation between the SM and NP parameters reads

\[ R_{NP} = -R_{SM} \cos 2(\theta - \phi_1) \pm \sqrt{1 - R_{SM}^2} \sin^2 2(\theta - \phi_1). \]
where $R_{SM}$ can be calculated in the SM box-diagram approximation:

$$R_{SM} = \frac{G_F^2 B_B f_B^2 M_B m_t^2}{6\pi^2 \Delta M} \eta_B F \left( \frac{m_t^2}{m_W^2} \right) |\xi_t|^2$$

(8)

with $\eta_B \approx F(m_t^2/m_W^2) \approx 0.55$. We see that there exist two solutions for $R_{NP}$.

The lepton $CP$ asymmetry $A_{SL}$ turns out to be:

$$\frac{A_{SL}}{C_m} = R_{SM} R_{NP} \left[ \text{Im} \left( \frac{\xi_u}{|\xi_t|} \right)^2 T_u + \text{Im} \left( \frac{\xi_c}{|\xi_t|} \right)^2 T_c + \text{Im} \left( \frac{\xi_t}{|\xi_t|} \right)^2 T_t \right] \cos(2\theta)$$

$$+ R_{SM}^2 \left[ \text{Im} \left( \frac{\xi_u}{\xi_t} \right)^2 T_u + \text{Im} \left( \frac{\xi_c}{\xi_t} \right)^2 T_c \right]$$

$$+ R_{SM} R_{NP} \left[ \text{Re} \left( \frac{\xi_u}{|\xi_t|} \right)^2 T_u + \text{Re} \left( \frac{\xi_c}{|\xi_t|} \right)^2 T_c + \text{Re} \left( \frac{\xi_t}{|\xi_t|} \right)^2 T_t \right] \sin(2\theta)$$

(9)

where $C_m \approx 1.3 \times 10^{-2}$. Clearly the second term of $A_{SL}$ comes purely from $M_{SM}^{12}$ itself and its magnitude is expected to be of $O(10^{-3})$ due to the absence of the $T_t$ contribution. The first and third terms of $A_{SL}$ arise from the interference between $M_{SM}^{12}$ and $M_{NP}^{12}$; but they depend on nonvanishing $\text{Im}(M_{SM}^{12})$ and $\text{Im}(M_{NP}^{12})$, respectively. For appropriate values of $\theta$ and $\phi_1$, magnitudes of both the first and third terms of $A_{SL}$ may be at the percent level! To obtain $|A_{SL}| \sim O(10^{-2})$, however, there should not be large cancellation between two dominant terms in Eq. (9).

The $CP$ asymmetry in $B_d \rightarrow J/\psi K_S$ can be calculated in the same framework. We obtain

$$A_{\psi K} = R_{SM} \sin(2\phi_1) + R_{NP} \sin(2\theta).$$

(10)

As $R_{NP}$, $R_{SM}$ and $\phi_1$, $\theta$ are dependent on one another through Eq. (7), $|A_{\psi K}| \leq 1$ is always guaranteed within the allowed parameter space.
Two interesting cases, corresponding to $\mathrm{Im} M_{12}^{\text{SM}} = 0$, $\mathrm{Im} M_{12}^{\text{NP}} \neq 0$ and $\mathrm{Im} M_{12}^{\text{NP}} = 0$, $\mathrm{Im} M_{12}^{\text{SM}} \neq 0$, have been numerically illustrated by Sanda and the author. It is found that $A_{\text{SL}}$ does have good chances to reach the percent level, and the correlation between $A_{\text{SL}}$ and $A_{\psi K}$ (as well as other CP asymmetries) does reflect the information from NP.

4 Summary

We have commented on the dependence of $\epsilon_B$ or $\epsilon_B$ on the KM phase convention. We emphasize that neither of them can prove much advantage in describing data of CP violation from $B^0$-$\bar{B}^0$ mixing. Also a simple framework has been presented for the analysis of possible NP contributions to $B^0$-$\bar{B}^0$ mixing and of their effects on $A_{\text{SL}}$ and other CP asymmetries. If we are lucky, we should be able to detect the lepton CP asymmetry at the percent level in the first-round experiments of $B$ factories.

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