Effect of Supersymmetric phases on the Direct CP Asymmetry of $B \rightarrow X_d\gamma$

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We investigate the effect of supersymmetric CP violating phases on the inclusive decay $B \rightarrow X_d\gamma$. Although such a decay contains a large background from $B \rightarrow X_s\gamma$, if isolated it may exhibit sizeable CP violation, both in the Standard Model (SM) and in the context of models beyond the SM. With unconstrained supersymmetric CP violating phases we show that the direct CP asymmetry ($A_{CP}$) lies in the region $-40\% \leq A_{CP} \leq 40\%$, where a positive asymmetry would constitute a clear signal of physics beyond the SM. Even if a direct measurement of $B \rightarrow X_s\gamma$ proves too difficult experimentally, its asymmetry contributes non-negligibly to the measurements of $A_{CP}$ for $B \rightarrow X_s\gamma$, and thus should be included in future analyses. We show that there may be both constructive and destructive interference between $A_{CP}^{d\gamma}$ and $A_{CP}^{s\gamma}$.

1 Introduction

Theoretical studies of rare decays of $b$ quarks have attracted increasing attention with the recent turn-on of the $B$ factories at KEK and SLAC. In this talk we are concerned with the rare decay $b \rightarrow d\gamma$ which proceeds via an electromagnetic penguin diagram, and is sensitive to the CKM matrix element $V_{td}$. The work on which this talk is based has been published in [1].

The current measurement of $A_{CP}$ for $b \rightarrow s\gamma$ by the CLEO Collaboration is sensitive to events from $b \rightarrow d\gamma$. Therefore knowledge of $A_{CP}$ for $b \rightarrow d\gamma$ is essential, in order to compare experimental data with the theoretical prediction in a given model.

We are interested in the effect of unconstrained supersymmetric (SUSY) CP violating phases on the inclusive decay BR($B \rightarrow X_d\gamma$). We will be working in the context of the effective SUSY model proposed in [2]. Such a model allows one to consider the full impact of the phases on the rare decays of $B$ mesons, while simultaneously satisfying the stringent bounds on the Electric Dipole Moments of the electron and neutron.

2 The decays $b \rightarrow d\gamma$ and $b \rightarrow s\gamma$

Much theoretical study has been devoted to the decay $b \rightarrow s\gamma$ due to its sensitivity to physics beyond the SM [3]. Exclusive channels ($B \rightarrow K_s\gamma$ etc.) and the inclusive channel have been measured at CLEO, ALEPH, BELLE and BaBar [4]. The related decay $b \rightarrow d\gamma$ has received less attention although is expected to be observed at the $B$ factories, at least in some exclusive channels.

Ref. [5] calculated BR($B \rightarrow X_d\gamma$) in the context of the SM. It was shown that the ratio $R$ defined by

$$R = \frac{BR(B \rightarrow X_d\gamma)}{BR(B \rightarrow X_s\gamma)}$$

is expected to be in the range $0.017 < R < 0.074$, corresponding to BR($B \rightarrow X_d\gamma$) of order $10^{-5}$ to $10^{-6}$. With $10^3$ $B\bar{B}$ pairs expected from the $B$ factories, one would be able to produce $10^2 \rightarrow 10^3$ $b \rightarrow d\gamma$ transitions. In the ratio $R$ most of the theoretical uncertainties cancel, and hence $R$ may provide a theoretically clean way of extracting the ratio $|V_{td}/V_{ts}|$.

The CP asymmetry ($A_{CP}$), defined by

$$A_{CP}^{d\gamma(s\gamma)} = \frac{\Gamma(B \rightarrow X_{d(s)}\gamma) - \Gamma(B \rightarrow X_{d(s)}\gamma)}{\Gamma(B \rightarrow X_{d(s)}\gamma) + \Gamma(B \rightarrow X_{d(s)}\gamma)} = \frac{\Delta \Gamma_{d(s)}}{\Gamma_{d(s)}}$$

is expected to lie in the range $-7\% \leq A_{CP}^{d\gamma} \leq -35\%$ in the SM [6], where the uncertainty arises from varying $\rho$ and $\eta$ in their allowed regions. Also included is the scale dependence ($\mu_b$) of $A_{CP}^{d\gamma}$ which occurs from varying $m_h/2 \leq \mu_b \leq 2m_b$. For definiteness we fix $\mu_b = 4.8$ GeV, and find $-5\% \leq A_{CP}^{d\gamma} \leq -28\%$. Therefore $A_{CP}^{d\gamma}$ is much larger than $A_{CP}^{s\gamma}$, ($\leq 0.6\%$). By estimating values for detection efficiencies, it has been argued in [7] that $A_{CP}^{d\gamma}$ may be statistically more accessible than $A_{CP}^{s\gamma}$, at least in the context of the SM. This analysis assumes that $B \rightarrow X_d\gamma$ can be clearly isolated from $B \rightarrow X_s\gamma$.

However, it is known that isolating the signal $B \rightarrow X_d\gamma$ would be an experimental challenge since $B \rightarrow X_s\gamma$ constitutes a serious background. [7] has suggested several ways to overcome this problem, e.g. demanding a higher

Note that our definition $A_{CP}$ contains a relative minus sign compared to that used in [8].
energy cut on $\gamma$, since $\gamma$ from $B \to X_d\gamma$ will be more energetic than that from $B \to X_s\gamma$. Energy cuts can be used to separate $b \to s\gamma$ events from charmed background since there is a high photon energy region that is inaccessible to charmed states because of the mass of the charm quarks. This method is not feasible for extracting $b \to d\gamma$ events from a $b \to s\gamma$ sample. Although the strange quark mass is larger than the down quark mass, the respective lightest hadronic single particle final states, $K^*$ and $\rho$, have almost the same mass (they actually overlap strongly). The lightest multi-particle states are $K\pi$ and $\pi\pi$, respectively, but even here effects such as bound state effects (neglected in) smear the spectra out over regions of the order of 200 MeV. These effects constitute one of the major theoretical uncertainties in the extraction of $BR(B \to X_d\gamma)$ from the measured part of the spectrum, and they make a separation of $b \to d\gamma$ and $b \to s\gamma$ via energy cuts impossible. A comparison of the photon energy spectra for $b \to s\gamma$ and $b \to d\gamma$ was made in, and showed that the photon spectra for both decays are very similar.

A more promising approach constitutes exclusive channels. The improved $K/\pi$ separation at the $B$ factories may enable the inclusive $B \to X_d\gamma$ decay to be reconstructed by summing over the relevant exclusive channels as done by CLEO in the measurement of $B \to X_s\gamma$. suggested using a semi-inclusive sample of $B \to \gamma + n\pi$ decays with a maximum of $n$ (say 5) mesons together with a corresponding measurement of $B \to \gamma + K + (n-1)\pi$. The ratio of the widths of the semi-inclusive samples would enable the total inclusive rate to be deduced to a very good approximation. Although the extraction of the branching ratio for $b \to d\gamma$ from exclusive channels might suffer additional uncertainties with respect to $b \to s\gamma$, the asymmetry should not be affected by these.

If $A_{CP}^{d\gamma}$ and $A_{CP}^{s\gamma}$ cannot be separated, then only their sum can be measured. In the context of the SM (with $m_s = m_d = 0$) the unitarity of the CKM matrix ensures that the sum is zero. This relation holds only for the short distance contribution, which is expected to be dominant (c.f. introduction). In the presence of new physics such a cancellation does not occur, as will be shown in section 4. As stressed earlier, a reliable prediction of $A_{CP}^{d\gamma}$ in a given model is necessary since it contributes to the measurement of $A_{CP}^{s\gamma}$. The CLEO result is sensitive to a weighted sum of CP asymmetries, given by:

$$A_{CP}^{exp} = 0.965 A_{CP}^{s\gamma} + 0.02 A_{CP}^{d\gamma} \quad (3)$$

The latest measurement stands at $-27\% < A_{CP}^{d\gamma} < 10\%$ (90\% c.l.) . The small coefficient of $A_{CP}^{d\gamma}$ is caused by the smaller $BR(B \to X_d\gamma)$ (assumed to be 1/20 that of $BR(B \to X_s\gamma)$) and inferior detection efficiencies, but may be partly compensated by the larger value for $A_{CP}^{s\gamma}$. We shall see that there can be both constructive and destructive interference between the two terms in eq. (3).

These effects will be especially important for measurements in future high luminosity runs of $B$ factories, in which the precision is expected to reach a magnitude where the $b \to d\gamma$ contribution becomes crucial. For integrated luminosities of 200 fb$^{-1}$ (2500 fb$^{-1}$) anticipates a precision of 3\%(1\%) in the measurement of $A_{CP}^{exp}$.

3 Results

We explore the effect of CP violating SUSY phases on the direct CP asymmetry of the inclusive decay $B \to X_d(s)\gamma$. We will show that the asymmetry $A_{CP}^{d\gamma}$ may be quite different from the SM prediction in a wide region of parameter space consistent with experimental bounds from the Electric Dipole Moment (EDM) and $BR(B \to X_s\gamma)$.

In our analysis we adopt the “effective SUSY” model, proposed in. It is instructive to consider the impact of unconstrained SUSY phases on the inclusive decay $B \to X_d\gamma$ by taking $A_1$ and $\mu$ complex. The same approach has been used in Ref., and it was shown that $A_{CP}^{d\gamma}$ may lie in the range $-16\% \leq A_{CP}^{d\gamma} \leq 16\%$.

We vary the (SUSY) parameters in reasonable ranges and respect the direct search lower limits on the masses of $t_1$, $\chi^\pm$ by discarding generated points that do not pass our cuts of $m_{t_1} > 90$ GeV and $m_{\chi^\pm} > 80$ GeV in addition to the cut on $C_7$ mentioned in Sec. 3. We vary $\rho$ and $\eta$ in the range allowed by present CKM fits for the SM. Note that in the effective SUSY model one should strictly only include the constraint from $|V_{ub}/V_{cd}|$, which corresponds to varying $\rho$ and $\eta$ in a semi-circular band in the $\rho - \eta$ plane. This enlarged parameter space has little effect on our graphs, except for Fig.3, which will be commented on below.

If the signal for the inclusive decay can be isolated then a positive asymmetry would be a clear sign of new physics. In Fig. we plot $A_{CP}^{d\gamma}$ against $m_{t_1}$, which clearly shows that a light $t_1$ may drive $A_{CP}^{d\gamma}$ positive, reaching maximal values close to +40%. For $t_1$ heavier than 250 GeV the $A_{CP}^{d\gamma}$ lies within the SM range, which is indicated by the two horizontal lines.

We note that our upper limit of +40% is larger than the maximum value of 21\% attained in. The inclusion of the SUSY phases has joined and expanded the two phenomenological regions found in, allowing CP asymmetries in the continuous region $-40\% \leq A_{CP}^{d\gamma} \leq 40\%$. In Fig. we show that the large positive asymmetries can be found anywhere in the interval $5 \leq \tan \beta \leq 30$, which is the region where the EDM constraint in is comfortably satisfied.
If the signals from $b \to s\gamma$ and $b \to d\gamma$ cannot be isolated then one must consider a combined signal. In Fig. 3 we plot $A_{CP}^{s\gamma}$ against $A_{CP}^{d\gamma}$. The maximum values for $A_{CP}$ agree with those found in [2]. It can be seen that there is an inaccessible region and the asymmetries can never simultaneously be zero e.g. for $A_{CP}^{s\gamma} \approx 0$, $|A_{CP}^{d\gamma}| \geq 3\%$. This can be explained from the fact that $A_{CP}^{s\gamma} \approx 0$ would require $C_7$ to have a sizeable imaginary part in order to cancel the large negative contribution from $\epsilon_p$. The corresponding effect on $A_{CP}^{d\gamma}$ would be to cause a sizeable deviation from its small SM value. Fig. 3 shows that both $A_{CP}^{s\gamma}$ and $A_{CP}^{d\gamma}$ can have either sign, resulting in constructive or destructive interference in eq. (3). If only the $|V_{ub}/V_{cd}|$ constraint is included in the CKM fits, the enlarged parameter space for $\rho$ and $\eta$ allows much smaller asymmetries for $A_{CP}^{d,s\gamma}$. This is because smaller values of $\eta$ are now allowed, which reduces the SM contribution to $A_{CP}^{d,s\gamma}$. The choice of $\eta \to 0$ would correspond to points in the previously inaccessible region.

In Fig. 3 we plot $\Delta \Gamma_d + \Delta \Gamma_s$ (defined in eq. (2)) against $\text{Im}(C_7)$. In the SM (as explained in Section 2) this sum would be exactly zero in the limit $m_b = m_s = 0$ (neglecting the small long distance contribution). From Fig. 3 it can be seen that $\Delta \Gamma_d + \Delta \Gamma_s$ is close to 0 if $C_7$ is real, the slight deviation being caused by the imaginary parts of the other Wilson coefficients. The effect of a non-zero $\text{Im}(C_7)$ causes sizeable deviations from zero.

In Fig. 3 we plot the $A_{CP}^{d\gamma}$ (defined in eq. (3)) against $A_{CP}^{\eta\gamma}$. The right hand plot shows a magnification of the area around the origin. The coefficient of $A_{CP}^{\eta\gamma}$ in eq. (3) assumes that $\text{BR}(b \to d\gamma) / \text{BR}(b \to s\gamma) = 20$. Since this ratio of BRs is $|V_{ub}/V_{us}|^2$, which in turn is a function of the variables $\rho$ and $\eta$, we replace the factor 1/20 by the above ratio of CKM matrix elements. If the contribution from $A_{CP}^{\eta\gamma}$ were ignored in eq. (3), then Fig. 3 would be a straight line through the origin. The $A_{CP}^{\eta\gamma}$ contribution broadens the line to a thin band of width $\approx 1\%$, an effect which should be detectable at proposed higher luminosity runs of the $B$ factories.

Note that the width of the line is determined by the amount of $b \to d\gamma$ admixture in the $b \to s\gamma$ sample, eq. (3). In the case of the CLEO measurement the admixture of $b \to d\gamma$ is about 2.5 times less than the “natural” admixture (ratio of the branching ratios). If the experimental analysis can be done with a natural admixture or even a $b \to d\gamma$ enriched sample, the width of the line would be correspondingly broader. Specifically, for the natural admixture the line would be broadened by a factor of 2.5, making $b \to d\gamma$ a 2.5% effect. This effect is the same magnitude as the precision attainable with an integrated luminosity of 200 fb$^{-1}$ at the $B$ factories [8]. At this luminosity it will therefore be possible to test the cancellation of the asymmetries as predicted by the SM.

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Figure 1: $A_{CP}^{d\gamma}$ against $m_{t_1}$

Figure 2: $A_{CP}^{d\gamma}$ against $\tan \beta$

Figure 3: $A_{CP}^{d\gamma}$ against $A_{CP}^{s\gamma}$

Figure 4: $\Delta \Gamma_d + \Delta \Gamma_s$ against $\text{Im}(C_7)$

Figure 5: Asymmetry measured by CLEO ($A_{CP}^{\exp}$) against $A_{CP}^{d\gamma}$

Figure 6: Asymmetry measured by CLEO ($A_{CP}^{\exp}$) against $A_{CP}^{s\gamma}$