Radiative B decays and new physics searches at \textit{BaBar}

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In this talk, a number of recent results on radiative $B$ decays from \textit{BaBar} are covered. Based on the full \textit{BaBar} dataset of 471 million $\Upsilon(4S) \to B\bar{B}$ events, the inclusive decays $B \to Xs\gamma$ and $B \to Xs\ell^+\ell^-$, as well as the exclusive decays $B \to K\pi^+\pi^-\gamma$ are measured for new physics searches.

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1. Introduction

Both the $b \to s \gamma$ and $b \to s \ell^+\ell^-$ transitions are flavor-changing neutral-current processes, and forbidden at tree level in the Standard Model (SM). The Feynmann diagrams representing these types of transitions must involve loops. In the effective field theory for $b \to s$ transitions, the effective Hamiltonian can be written conventionally as $H_{\text{Eff}} \propto \sum_{i=1}^{10} C_i \mathcal{O}_i$, which factorizes short-distance physics represented by the Wilson coefficients $C_i$ from long-distance effects. New physics beyond the SM brings in new loops for $b \to s$ transitions, and may change the SM values of Wilson coefficients.

During its entire data-taking period from 1999 till 2008, the BaBar detector [1] collected $\sim 471$ million $B\bar{B}$ pairs at the $\Upsilon(4S)$ resonance with the PEP-II asymmetric energy $e^+ e^-$ collider. Based on the full BaBar dataset, we present here the search for direct $CP$ violation in $B \to X_s \gamma$ using a sum of exclusive final states, as well as the time-dependent analysis of $B^0 \to K^0 \pi^+ \pi^- \gamma$ and the study of the $K^+ \pi^- \pi^+$ system in the decay $B^+ \to K^+ \pi^- \pi^+ \gamma$. Finally we present the measurement of the $B \to X_s \ell^+\ell^-$ branching fraction (BF) and search for direct $CP$ violation using a sum of exclusive final states. Here $X_s$ represents any hadronic system with one unit of strangeness.

For all the BaBar analyses presented here, the major backgrounds are either from $e^+ e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum events or from combinatorial $B\bar{B}$ events. Different types of multivariate classifiers, such as a Fisher discriminant, boosted decision trees (BDT), and random forests, are trained for the background suppression. Furthermore, we distinguish a fully reconstructed $B$ candidate from backgrounds with energy-substituted mass $m_B = \sqrt{E_{\text{CM}}^2/4 - p_B^2}$, and the energy difference $\Delta E = E_B^* - E_{\text{CM}}/2$, where $p_B^*$ and $E_B^*$ are the reconstructed $B$ momentum and energy in the $\Upsilon(4S)$ center-of-mass (CM) frame, respectively, and $E_{\text{CM}}$ is the total CM energy.

2. Search for direct $CP$ violation in $B \to X_s \gamma$ using a sum of exclusive final states

The direct $CP$ asymmetry ($A_{CP}$) for the sum of exclusive final states of $B \to X_s \gamma$ is measured by:

$$A_{CP}(B \to X_s \gamma) = \frac{\Gamma_{B^+ / B^- \to X_s \gamma} - \Gamma_{B^0 / B^0 \to X_s \gamma}}{\Gamma_{B^+ / B^- \to X_s \gamma} + \Gamma_{B^0 / B^0 \to X_s \gamma}}.$$  \hspace{1cm} (2.1)

In the SM, $A_{CP}$ is expected to be small and within a range of $-0.6\% < A_{CP}^{SM} < 2.8\%$ [2]. Measuring the difference in $A_{CP}$ in charged and neutral $B$ mesons $\Delta A_{X_s \gamma} = A_{B^+ \to X_s \gamma} - A_{B^0 / B^0 \to X_s \gamma}$ is proposed to be another test of the SM. $\Delta A_{X_s \gamma}$ depends on two Wilson coefficients $C_{7\gamma}$ and $C_{8\gamma}$ representing the electromagnetic dipole and the chromo-magnetic dipole transitions, respectively, according to the relationship [2]:

$$\Delta A_{X_s \gamma} \approx 0.12 \times \frac{\tilde{\Lambda}_{78}}{100 \text{ MeV}} \text{Im}(C_{8\gamma}/C_{7\gamma}),$$  \hspace{1cm} (2.2)

where the interference amplitude $\tilde{\Lambda}_{78}$ is known to be within the range $17 \text{ MeV} < \tilde{\Lambda}_{78} < 190 \text{ MeV}$. In the SM, we expect $\Delta A_{X_s \gamma} = 0$ as the two Wilson coefficients $C_{8\gamma}$ and $C_{7\gamma}$ are real. Experimentally, $C_{8\gamma}$ is not as well constrained as $C_{7\gamma}$. Together with existing knowledge on $C_{7\gamma}$, a measurement on $\Delta A_{X_s \gamma}$ can place a constraint on $C_{8\gamma}$. \hspace{1cm} (2.2)

\footnote{Charge conjugation is implied throughout unless explicitly noted.}
Radiative $B$ decays and new physics searches at $B\bar{B}$

Liang SUN

**Figure 1:** Fits to the $\bar{B}$ and $B$ samples.

**Figure 2:** (a) The minimum $\chi^2$ for given $\text{Im}\left(C_{8g}/C_{7}\gamma\right)$ from all possible values of $\tilde{\Lambda}_{78}$, also shown are the 68% and 90% confidence intervals for $\text{Im}\left(C_{8g}/C_{7}\gamma\right)$; (b) The 68% and 90% CLs for $\text{Im}\left(C_{8g}/C_{7}\gamma\right)$ as a function of $\tilde{\Lambda}_{78}$.

In this analysis [3], we fully reconstruct $B$ meson decays in 16 self-tagging final states as listed in Ref. [3] where the $B$ flavor can be determined from the final state particles.

The raw asymmetry is extracted via fitting simultaneously to the $m_{ES}$ distributions of $B$ and $\bar{B}$ tagged samples, as demonstrated in Fig. 1, which is further corrected for detector related effects to get $A_{CP}$. We measure $A_{CP} = +(1.7 \pm 1.9[^{\text{stat.}}] \pm 1.0[^{\text{syst.}}])\%$, which is the most precise to date and agrees with the SM. Through fitting simultaneously to the separate charged and neutral $B$ samples, we also provide the first measurement on $\Delta A_{X\gamma}$:

$$\Delta A_{X\gamma} = +(5.0 \pm 3.9[^{\text{stat.}}] \pm 1.5[^{\text{syst.}}])\%,$$

which is consistent with the SM expectation of zero. We compare the measured $\Delta A_{X\gamma}$ with the prediction based on the relationship in Eq. 2.2 for given $\text{Im}(C_{8g}/C_{7}\gamma)$ and $\tilde{\Lambda}_{78}$ to calculate the minimum $\chi^2$, as shown in Fig. 2(a). The ranges of $\text{Im}(C_{8g}/C_{7}\gamma)$ and $\tilde{\Lambda}_{78}$ that yield the minimum $\chi^2$ less than 1 and 4 are used to obtain the 68% and 90% confidence limits (CLs) shown in Fig. 2(b).

Using the extremes in Fig. 2(b) for all permitted values of $\tilde{\Lambda}_{78}$, we conservatively set $\text{Im}(C_{8g}/C_{7}\gamma)$:

$$0.07 \leq \text{Im}(C_{8g}/C_{7}\gamma) \leq 4.48 \text{ @68\% CL}; \ -1.64 \leq \text{Im}(C_{8g}/C_{7}\gamma) \leq 6.52 \text{ @90\% CL}.$$

3. **Studies of $B \to K\pi\pi\gamma$ decays**

We measure CP asymmetry in the decay $B^0 \to K^0_s\rho^0\gamma$ as a function of $B^0-\bar{B}^0$ decay-time difference $\Delta t$, which is defined as:

$$A_{CP} \equiv \frac{\Gamma(B^0(\Delta t) \to f_{CP}\gamma) - \Gamma(\bar{B}^0(\Delta t) \to f_{CP}\gamma)}{\Gamma(B^0(\Delta t) \to f_{CP}\gamma) + \Gamma(\bar{B}^0(\Delta t) \to f_{CP}\gamma)} = S_{K^0_s\rho^0\gamma} \sin(\Delta m_d\Delta t) - C_{f_{CP}\rho^0\gamma} \cos(\Delta m_d\Delta t),$$
where $\Delta m_d$ is the $B^0\bar{B}^0$ oscillation frequency fixed to the measurement in Ref. [4], while $C_{K_S^0\rho^0\gamma}$ and $S_{K_S^0\rho^0\gamma}$ are the direct and mixing-induced $CP$ asymmetry parameters, respectively.

Experimentally, for the hadronic part of $B^0 \rightarrow K^0_s \pi^+ \pi^- \gamma$ final state, as $\rho^0(770)$ possesses a large natural width, a large amount of irreducible background events from non-$CP$ eigenstates ($K^{\pm \pm}\pi^\mp$) will lie underneath the $\rho^0(770)$ resonance from our $B \rightarrow K_S^0\rho^0(\rightarrow \pi^+\pi^-)\gamma$ signal decay, and thus dilute our $CP$ parameter $S_{K_S^0\rho^0\gamma}$. The dilution factor is defined as $D_{K_S^0\rho^0\gamma} = \frac{S_{K_S^0\rho^0\gamma}}{S_{K_S^0\rho^0\gamma}}$, where $S_{K_S^0\pi^+\pi^-\gamma}$ is the effective value of the mixing-induced $CP$ asymmetry measured based on all $B^0 \rightarrow K_S^0\pi^+\pi^-\gamma$ data events. In order to measure $S_{K_S^0\rho^0\gamma}$ an amplitude study on the hadronic system of $B^0 \rightarrow K_S^0\pi^+\pi^-\gamma$ events is needed here to extract $D_{K_S^0\rho^0\gamma}$. However this turns out to be a rather difficult task due to limited statistics. We therefore turn to the statistically more abundant sample of charged decays $B^+ \rightarrow K^+\pi^-\pi^\gamma$ for the determination of the dilution factor under the assumption of isospin symmetry.

The fits to $B^+ \rightarrow K^+\pi^-\pi^\gamma$ events undergo in three steps: first we perform a three-dimensional fit using $m_{ES}$, $\Delta E$, and the Fisher discriminant output to unfold the signal distributions of invariant masses $m_{K\pi\pi}$ and $m_{K\pi}$. Then we fit to the $m_{K\pi\pi}$ distribution from the first step to determine the BFs of different kaonic resonances, such as $K_1(1270)^+$, $K_2^+(1430)^+$, etc. The final fit is to the $m_{K\pi}$ distribution to determine the amplitudes and BFs of the intermediate resonances ($K^0(892)$, $\rho(770)^0$, etc.) decaying to $K^+\pi^-$ and $\pi^+\pi^-$. From the measured branching fractions in the last step of fit we compute the dilution factor as $D_{K_S^0\rho^0\gamma} = 0.549^{+0.096}_{-0.094}$, where the uncertainties incorporate both statistical and systematic contributions.

As shown in Fig. 3, we perform a four-dimensional fit to the data from the neutral mode $B^0 \rightarrow K_S^0\pi^+\pi^-\gamma$, to extract the $CP$ asymmetry parameters. With the measured dilution factor from the
we have B charged mode, we find for the B decay two-dimensional fit to the distributions of theory predictions. Fits to the distributions of Figure 4: Radiative B decays and new physics searches at B of B to be event calculated based on the response of background) (12.9 < q^2 < 14.2 GeV^2/c^4) to suppress signal-like charmonium backgrounds with J/ψ (ψ(2S)) from B decays. The entire event selection criteria represent ~70% of the inclusive B → X_s ℓ^+ ℓ^- rate with the invariant mass of the hadronic system m_X < 1.8 GeV/c^2, accounting for K^0 modes, K^0 → π^0 π^0, and π^0 Dalitz decays in our signal reconstruction efficiencies. We also extrapolate for the missing final states, and those with m_X > 1.8 GeV/c^2, using JETSET fragmentation [7] and theory predictions.

We measure the total BF and partial BFs in different ranges of q^2 or m_X by performing a two-dimensional fit to the distributions of m_ES and likelihood ratio L_R, which is defined as L_R ≡ \mathcal{P}_S/(\mathcal{P}_S + \mathcal{P}_B) with \mathcal{P}_S (\mathcal{P}_B) as the probability for a correctly-reconstructed signal (B\bar{B} background) event calculated based on the response of B\bar{B} BDT. The L_R distributions for signal and B\bar{B} background events peak around one and zero, respectively. A fit example is shown in Fig. 4 for B \rightarrow X_s e^+ e^- events with 2.0 < q^2 < 4.3 GeV^2/c^4.

Our measured partial BF results are shown in Fig. 5. We find the total BF for q^2 > 0.1 GeV^2/c^4 to be B(B \rightarrow X_s e^+ e^-) = (6.73^{+0.70+0.34}_{-0.63-0.25} \pm 0.50) \times 10^{-6}, which is less than 2σ above the SM prediction of B^SM(B \rightarrow X_s e^+ e^-) = (4.6^{+0.8}_{-0.7}) \times 10^{-6} [8]. In the low mass range with 1 < q^2 < 6 GeV^2/c^4, we have B^{low}(B \rightarrow X_s e^+ e^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}, which is in good agreement with the SM predictions of B^{low}_{SM}(B \rightarrow X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6} and B^{low}_{SM}(B \rightarrow X_s μ^+ μ^-) = (1.59 \pm 0.11) \times 10^{-6} [9]. And in the high mass range with q^2 > 14.2 GeV^2/c^4, our result of B^{high}(B \rightarrow X_s e^+ e^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00) \times 10^{-6} is about 2σ higher than the SM predictions of B^{high}_{SM}(B \rightarrow X_s e^+ e^-) = (0.21 \pm 0.07) \times 10^{-6} and B^{high}_{SM}(B \rightarrow X_s μ^+ μ^-) = (0.24 \pm 0.07) \times 10^{-6} [9]. In all the three results listed above, the first uncertainties are statistical, the second experimental systematics and the third model-dependent systematics.

4. Branching fractions and direct CP asymmetry in B \rightarrow X_s ℓ^+ ℓ^- using a sum of exclusive final states

In this analysis[6], the inclusive decay B \rightarrow X_s ℓ^+ ℓ^- is studied in 20 exclusive final states each comprises one kaon and at most two pions, ℓ^+ ℓ^- is either e^+ e^- or μ^+ μ^-, as listed in Ref. [6]. We reject events with dilepton mass squared q^2 ≡ m_{ℓℓ}^2 within a range of 6.8 < q^2 < 10.1 GeV^2/c^4 to suppress signal-like charmonium backgrounds with J/ψ (ψ(2S)) from B decays. The entire event selection criteria represent ~70% of the inclusive B → X_s ℓ^+ ℓ^- rate with the invariant mass of the hadronic system m_X < 1.8 GeV/c^2, accounting for K^0 modes, K^0 → π^0 π^0, and π^0 Dalitz decays in our signal reconstruction efficiencies. We also extrapolate for the missing final states, and those with m_X > 1.8 GeV/c^2, using JETSET fragmentation [7] and theory predictions.

We measure the total BF and partial BFs in different ranges of q^2 or m_X by performing a two-dimensional fit to the distributions of m_ES and likelihood ratio L_R, which is defined as L_R ≡ \mathcal{P}_S/(\mathcal{P}_S + \mathcal{P}_B) with \mathcal{P}_S (\mathcal{P}_B) as the probability for a correctly-reconstructed signal (B\bar{B} background) event calculated based on the response of B\bar{B} BDT. The L_R distributions for signal and B\bar{B} background events peak around one and zero, respectively. A fit example is shown in Fig. 4 for B \rightarrow X_s e^+ e^- events with 2.0 < q^2 < 4.3 GeV^2/c^4.

Our measured partial BF results are shown in Fig. 5. We find the total BF for q^2 > 0.1 GeV^2/c^4 to be B(B \rightarrow X_s e^+ e^-) = (6.73^{+0.70+0.34}_{-0.63-0.25} \pm 0.50) \times 10^{-6}, which is less than 2σ above the SM prediction of B^SM(B \rightarrow X_s e^+ e^-) = (4.6^{+0.8}_{-0.7}) \times 10^{-6} [8]. In the low mass range with 1 < q^2 < 6 GeV^2/c^4, we have B^{low}(B \rightarrow X_s e^+ e^-) = (1.60^{+0.41+0.17}_{-0.39-0.13} \pm 0.18) \times 10^{-6}, which is in good agreement with the SM predictions of B^{low}_{SM}(B \rightarrow X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6} and B^{low}_{SM}(B \rightarrow X_s μ^+ μ^-) = (1.59 \pm 0.11) \times 10^{-6} [9]. And in the high mass range with q^2 > 14.2 GeV^2/c^4, our result of B^{high}(B \rightarrow X_s e^+ e^-) = (0.57^{+0.16+0.03}_{-0.15-0.02} \pm 0.00) \times 10^{-6} is about 2σ higher than the SM predictions of B^{high}_{SM}(B \rightarrow X_s e^+ e^-) = (0.21 \pm 0.07) \times 10^{-6} and B^{high}_{SM}(B \rightarrow X_s μ^+ μ^-) = (0.24 \pm 0.07) \times 10^{-6} [9]. In all the three results listed above, the first uncertainties are statistical, the second experimental systematics and the third model-dependent systematics.
In 14 self-tagging final states as listed in Ref. [6], we search for the direct $CP$ asymmetry in $B \to X_s \ell^+ \ell^-$ which is defined in the same manner as $A_{CP}(B \to X_s \gamma)$ in Eq. 2.1. $A_{CP}(B \to X_s \ell^+ \ell^-)$ is expected to be well below 1% in the SM [10]. We find the total $A_{CP}$ for $q^2 > 0.1$ GeV$^2$/c$^4$ to be $A_{CP}(B \to X_s \ell^+ \ell^-) = 0.04 \pm 0.11$[stat.] $\pm 0.01$[syst.]. We also measure $A_{CP}$ in different $q^2$ regions, and find all the results to be consistent with zero as expected in the SM.

5. Summary

With the full BaBar dataset of 471 million $B\bar{B}$ pairs, we perform a series of interesting measurements in radiative $B$ decays recently. Our direct $A_{CP}(B \to X_s \gamma)$ result is the most precise result to date and agree with the SM. The measured mixing-induced $CP$ parameter for $B^0 \to K_S^0 \rho^0 \gamma$ is found to be compatible with the SM expectation. Our $B(B \to X_s \ell^+ \ell^-)$ and direct $A_{CP}(B \to X_s \ell^+ \ell^-)$ results are generally consistent with the SM predictions, however some tensions exist for the total BF and partial BF in the region of $q^2 > 14.2$ GeV$^2$/c$^4$.

References


