Search for Rare Decays of $B$ Mesons at $B$-Factories

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Radiative penguin $B$ meson decays with $b \to s \gamma$ and $b \to d \gamma$ transitions are a powerful probe of physics beyond the Standard Model (SM). Because their rates can be determined to high precision, any deviation from the SM expectation is a hint of new physics. Such deviations might arise due to hypothetical heavy particles in the loop, such as Supersymmetric quarks or bosons or a charged Higgs. Using data from the BAGAR experiment, we report the inclusive and semi-inclusive $b \to s \gamma$ branching fraction, along with measured observables such as $E_{\gamma}$ and $A_{CP}$. Furthermore, the branching fraction measurements by both the BAGAR and Belle experiments of the exclusive $B \to \pi l^+ l^-$, $B^0 \to \eta l^+ l^-$ and $B \to h^* \nu \bar{\nu}$, where $h = K^*, \pi, \rho$ or $\phi$, are also reported. The BAGAR results on the invisible decays of heavy charmonium states ($J/\psi$ and $\psi(2S)$) in $B \to K^* \pi^0$ are also discussed.

1 Overview and Theoretical Motivation

Flavour Changing Neutral Current (FCNC) $B$ decays are governed by an interplay between the weak and strong interactions. Searches for FCNC decays can provide experimental constraints on the Wilson coefficients and matrix elements that constitute the electroweak effective Hamiltonian, and are thus a stringent test of the SM. Various new physics models, such as the two Higgs doublet model, can alter physical observables for these decays, including the branching fraction and CP asymmetry $^1$. In addition, invisible decays of heavy quarkonium states ($J/\psi$ and $\psi(2S)$) in $B \to K^* \pi^0$ are also discussed.

2 $b \to s \gamma$

In the Standard Model, the radiative decay $b \to s \gamma$ occurs via a 1-loop penguin diagram with a branching fraction at next-to-next leading order of $(3.15 \pm 0.23) \times 10^{-4}$. The challenge in this search is to make the measurement as inclusive as possible while suppressing large background levels, shown in Fig 1, caused mainly by continuum events where $e^+$ and $e^-$ decay into a pair of quarks instead of forming a $\Upsilon(4S)$ resonance. The $b \to s \gamma$ branching fraction can be measured using a fully inclusive approach, where neither the final $X_s$ state from the signal $B$ nor the recoiling $B$ meson are reconstructed $^a$. Another technique is the semi-inclusive approach, in which as many exclusive $X_s$ states as possible are reconstructed and combined, but the recoiling $B$ meson is not reconstructed.

$^a$The resulting $\Upsilon(4S)$, from $e^+ e^-$ collisions decays into a pair of $B$ mesons. The signal $B$ is defined as the one where the $b$ quark decays into $s$ quark and a radiating photon.
2.1 Fully-Inclusive $b \to s \gamma$ measurement

The fully-inclusive $b \to s \gamma$ branching fraction is measured at BABAR using a sample of $383 \times 10^6 B\bar{B}$ pairs. Events with at least 3 charged tracks are selected, to ensure the decay is hadronic, along with requirements on an energetic photon in the center-of-mass frame, $1.53 < E_\gamma^* < 3.5$ GeV. The recoiling $B$ meson is identified with a lepton from $B \to X_c \ell \nu_\ell$ decays, where $\ell = e$ or $\mu$. Event topology requirements are applied to further suppress continuum backgrounds. The background contribution, shown in Fig 1, is estimated using off-resonance data and MC simulation and then subtracted to obtain the raw $E_\gamma$ distribution. The resulting branching fraction is $(3.21 \pm 0.15_{(stat)} \pm 0.29_{(sys)} \pm 0.08_{(theory)}) \times 10^{-4}$ for $1.8 < E_\gamma < 2.9$ GeV, where $E_\gamma$ here is measured in the signal $B$ rest frame. Furthermore, the CP asymmetry, $A_{CP}$, is determined by dividing the selected events into $B$ and $\bar{B}$ samples, according to the charge of the tagging lepton. The BABAR result is found to be $A_{CP}(B \to X_s \gamma) = 0.057 \pm 0.060_{stat} \pm 0.018_{sys}$. Both the branching fraction and the CP asymmetry are in excellent agreement with the SM expectation. In addition, the shape of the photon spectrum provides insight into the dynamics of the $b$ quark inside the $B$ meson. In this inclusive analysis, the measured $E_\gamma$ spectrum is unfolded, by accounting for detector effects and Doppler smearing, to extract the true $E_\gamma$ spectrum in the signal $B$ rest frame.

2.2 Semi-Inclusive $b \to s \gamma$ measurement

Another way to determine the $b \to s \gamma$ branching fraction is using a semi-inclusive approach, where the $X_s$ system is reconstructed using a sum of exclusive states. Due to large backgrounds from high-multiplicity $X_s$ decays, only 60% of the $X_s$ final states can be fully reconstructed, resulting in significant efficiency uncertainties. However, reconstructing the $X_s$ system determines the $B$ meson momentum and thus kinematic constraints can be used to suppress the large background levels. In this analysis, the full BABAR dataset, corresponding to $470 \times 10^6 B\bar{B}$ pairs, is used. The $X_s$ state is reconstructed in one of 38 exclusive modes, and then combined with an energetic photon, $1.6 < E_\gamma^* < 3.0$ GeV, to form a $B$ candidate. To account for the missing branching fraction in the fragmentation of the $X_s$ system, the measured rate of $X_s$ decays is compared between data and Monte Carlo. The signal yield is extracted using a fit to the $m_{ES}$ distribution in bins of $m_{X_s}$, as shown in Fig 2, where $m_{ES}$ is the energy substituted mass of the $B$ meson given by $m_{ES} = \sqrt{E_{CM}^2 - p_B^2}$. Here, $E_{CM}$ is the energy of the beam in the CM frame and $p_B$ is the momentum of the $B$ meson. The resulting branching fraction is $\mathcal{B}(B \to X_s \gamma) = (3.29 \pm 0.19 \pm 0.48) \times 10^{-4}$, in agreement with the SM. In addition, $A_{CP}$ is also measured in this analysis, for neutral, charged and all $B$ meson decays. The difference between the charged and neutral asymmetry, $\delta A_{X_s \gamma}$, is further calculated and found to be...
The decays, $B \to \pi l^+l^-$ and $B \to \eta l^+l^-$ where $l = e$ or $\mu$, are also FCNC processes, suppressed by a CKM factor of $|V_{td}/V_{ts}|^2 = 0.04$ compared to $B \to K \ell^+\ell^-$. Using the full BABAR dataset, $B$ candidates are reconstructed from a hadron and di-lepton candidate, which are fit to a common vertex. Background events, where the leptons originate from a $c\bar{c}$ resonance, are eliminated by applying a $J/\psi$ and $\psi(2S)$ veto. The signal yield is then extracted from a fit to the $m_{ES}$ and $\Delta E$ distributions, where $\Delta E$ is defined as the difference between the beam energy and that of the $B$ meson. Even though a significant signal was not observed, the limit on $B \to \pi\ell^+\ell^-$ is improved and currently within factor of 3 of the SM expectation. In addition, the results for the $\pi^0 \ell^+\ell^-$, $\pi^+\mu^+\mu^-$, and $\pi^0 e^+e^-$ channels are the best limits to date.

4. $B \to h^{(*)}\nu\bar{\nu}$

The SM prediction for $B(B \to h^{(*)}\nu\bar{\nu})$ decays is of order $10^{-6}$. Various new-physics scenarios predict massive particles that could contribute additional loop diagrams to the decay and thus modify the branching fraction. The search for these decays is conducted by both the BABAR and Belle experiments, using a hadronic reconstruction technique. With this technique, one $B$ meson, $B_{tag}$, is reconstructed exclusively via hadronic modes. The remaining information in an event is then attributed to the other $B$ meson, $B_{sig}$, on which the search for $B \to h^{(*)}\nu\bar{\nu}$ is done.

4.1 $B \to h^{(*)}\nu\bar{\nu}$: Belle

Using a sample of $770 \times 10^6 B\bar{B}$ pairs, the $B_{tag}$ is reconstructed via 1104 exclusive modes. A light meson $h^*$ is then required on the $B_{sig}$ side, where $h^{(*)} = K^+, K^{*+}, K^{*0}, \pi^+, \pi^0, \rho, \rho^+$, and $\phi$. After reconstructing the $B_{tag}$ and light meson, a signal event is required to have no additional tracks or $\pi^0$ candidates. To remove backgrounds from $b \to c$ transitions, a cut on the $h^*$ momentum in the $B_{sig}$ rest frame is applied, $1.6 < p_{h^*} < 2.5$ GeV/c. The signal yield is then obtained by fitting the $E_{ECL}$ distribution in the range $0 < E_{ECL} < 1.2$ GeV, where $E_{ECL}$ is the sum energy of all clusters in the electromagnetic calorimeter that are not associated with neither the $B_{tag}$ nor the $h^*$. The resulting $B \to h^{(*)}\nu\bar{\nu}$ branching fraction limits are currently above the SM expectation, and allow contributions from new physics. Furthermore, the limits for $K^{*+}\nu\bar{\nu}, \pi^+\nu\bar{\nu}, \pi^0\nu\bar{\nu}$ and $\rho^0\nu\bar{\nu}$ are the most stringent constraints to date.
4.2 $B \to h^* \nu \overline{\nu}$: BaBar

In this analysis, the $B_{tag}$ is reconstructed using 1680 exclusive hadronic modes. The light meson $h^{(*)}$ is either a $K^0$, $K^+$, $K^{*0}$ or $K^{*+}$. Events with additional tracks or clusters are vetoed once the $B_{tag}$ and $K^{(*)}$ are identified. Backgrounds, from $B \to D^* \ell \nu$ decays are reduced by applying a tight cut on $E_{\text{extra}}$ (see Fig 3), the sum energy of all clusters with a center-of-mass energy greater than 50 MeV. The signal yield is then determined using the $s_B$ distribution, shown in Fig 3, for the region $s_B < 0.3$. Here, $s_B = q^2/m_B^2$, where $q^2$ is the squared magnitude of the four-momentum transferred from the $B$ meson to the neutrino pair and $m_B$ is the mass of the $B$ meson. The resulting branching fraction limits include the most stringent upper limit and first lower limit on $B(J/\psi \to \nu \nu) < 3.9 \times 10^{-3}$ and $B(\psi(2S) \to \nu \nu) < 15.5 \times 10^{-3}$. The search for $\psi(2S) \to \nu \nu$ is the first to be ever performed.

4.3 $J/\psi \to \nu \overline{\nu}$ and $\psi(2S) \to \nu \nu$

Invisible decays of charmonium states, such as $J/\psi$ and $\psi(2S)$, in $B \to K^{(*)} c \overline{c}$ have the same final state signature as $B \to K^* \nu \overline{\nu}$. In the Standard Model, the decays $J/\psi \to \nu \overline{\nu}$ and $\psi(2S) \to \nu \overline{\nu}$ are highly suppressed. However, extensions to the SM, such as spontaneously-broken SUSY and light dark matter, can considerably increase the branching fraction. Using the same signal selection as in the $B \to K^{(*)} \nu \overline{\nu}$ analysis, the search for $J/\psi \to \nu \overline{\nu}$ and $\psi(2S) \to \nu \overline{\nu}$ is performed at BaBar. After cutting on $E_{\text{extra}}$, the mass recoiling against the $K^{(*)}$ candidate is calculated. A cut is then applied on the recoiling mass spectrum about the $J/\psi$ and $\psi(2S)$ resonances to obtain the signal yield. The upper limits are found to be $B(J/\psi \to \nu \overline{\nu}) < 3.9 \times 10^{-3}$ and $B(\psi(2S) \to \nu \overline{\nu}) < 15.5 \times 10^{-3}$. The search for $\psi(2S) \to \nu \overline{\nu}$ is the first to be ever performed.

5 Conclusion

The large samples of $B\overline{B}$ pairs collected by both the BaBar and Belle experiments provide an excellent tool for precision tests of the Standard Model. These samples also allow for a wide range of new physics searches. $b \to s$ and $b \to d$ transitions are investigated using various inclusive and exclusive modes. The inclusive results are in excellent agreement with the SM, while the limits obtained, for many of the exclusive modes, are the most stringent to date.
References