\[ B \to X_s \gamma \text{ and } B \to X_s \ell^+ \ell^- \text{ at BABAR} \]

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**Representing the BABAR collaboration**

We present new \( B \to X_s \gamma \) measurements using both a fully inclusive approach and a sum of 38 exclusive final states. We update total and partial branching fractions, photon energy moments and the CP asymmetry. We extract the \( b \) quark mass and the kinetic energy of the \( b \) quark inside the \( B \) meson. For \( B \to K^{(*)} \ell^+ \ell^- \) decays, we present our final results on branching fractions, isospin asymmetries, CP violation asymmetry and lepton flavor ratios. For \( B \to K^{(*)} \ell^+ \ell^- \) modes, we have updated the angular analysis to determine the \( K^* \) longitudinal polarization and the lepton forward-backward asymmetry using the full BABAR data sample.

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1. Introduction

The decays $B \to X_S\gamma$ and $B \to K^{(*)}\ell^+\ell^-$, where $\ell^+\ell^-$ is $e^+e^-$ or $\mu^+\mu^-$, are flavor-changing neutral-current processes that are forbidden in the Standard Model (SM) at tree level. They are described by an effective Hamiltonian that factorizes short-distance contributions from long-distance effects. The $B \to X_S\gamma$ decay proceeds via the electromagnetic penguin diagram in which the short-distance part is determined by the effective Wilson coefficient $C_{\gamma}^{eff}$. In $B \to K^{(*)}\ell^+\ell^-$ modes, the $Z$ penguin and the box diagram also contribute whose short-distance parts are parametrized in terms of the effective Wilson coefficients $C_9^{eff}$ (vector part) and $C_{10}^{eff}$ (axial-vector part). Physics beyond the SM introduces new loops and box diagrams with new particles (e.g. charged Higgs boson, supersymmetric particles) that may modify the effective Wilson coefficients. In addition, scalar and pseudo scalar diagrams may contribute introducing new Wilson coefficients $C_5$ and $C_7$, respectively. To determine the Wilson coefficients precisely, we need to measure many observables in different modes. These rare decays probe New Physics at a scale of a few TeV.

2. $B \to X_S\gamma$

BABAR has updated the $B \to X_S\gamma$ measurements both in a fully inclusive and a semi-inclusive analysis using $383 \times 10^6 \, B\bar{B}$ events [1] and $471 \times 10^6 \, B\bar{B}$ events [2], respectively. In the SM at $\mathcal{O}(\alpha_{em}^2)$, the branching fraction is predicted to be $\mathcal{B}(B \to X_S\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for photon energies in the $B$-rest frame, $E_\gamma > 1.6$ GeV [3]. The measurement of $\mathcal{B}(B \to X_S\gamma)$ provides constraints on the charged Higgs mass $m_{H^\pm}$. The shape of the $E_\gamma$ spectrum depends on the $B$ quark mass $m_b$ and its momentum inside the $B$ meson. The shape function is expected to be similar to that for $B \to X_0\ell\nu$. Thus, precise measurements of the $E_\gamma$ spectrum help us with extracting $|V_{ub}|$.

In the fully inclusive analysis, we update total and partial branching fractions, photon energy moments and the $B \to X_{S+q}\gamma$ CP asymmetry [1]. To suppress $e^+e^- \to q\bar{q} \, (u,d,s,c)$ continuum and $B\bar{B}$ backgrounds, we tag the recoiling $B$ in semileptonic decays and use optimized $\pi^0$ and $\eta$ vetoes, missing energy requirements and the output of two neural networks. For a signal efficiency of 2.5%, the efficiency for accepting continuum ($B\bar{B}$) background is reduced to $5 \times 10^{-6}$ ($1.3 \times 10^{-4}$). We estimate the residual continuum background by studying data taken 40 MeV below the $T(4S)$ peak. Figure 1 (left) shows the $B \to X_S\gamma$ partial branching fraction after background subtraction and correcting for efficiency, resolution effects and Doppler smearing. For comparison, we show the predicted $E_\gamma$ spectrum in the kinematic scheme using HFAG world averages for the shape function parameters [4]. For $E_\gamma > 1.8$ GeV, BABAR measures a total branching fraction of $\mathcal{B}(B \to X_S\gamma) = (3.21 \pm 0.15_{stat} \pm 0.29_{sys} \pm 0.08_{mod}) \times 10^{-4}$ where uncertainties are statistical, systematic and model, respectively. This is in good agreement with previous measurements [5, 6, 7]. After extrapolation to $E_\gamma > 1.6$ GeV, the branching fraction increases to $\mathcal{B}(B \to X_S\gamma) = (3.31 \pm 0.16_{stat} \pm 0.30_{sys} \pm 0.09_{mod}) \times 10^{-4}$, in good agreement with the SM prediction. We use this result to constrain new physics in the type II two-Higgs doublet model [8] excluding $m_{H^\pm} < 327$ GeV/c^2 at 95% confidence level (CL) independent of tan$\beta$.

For $E_\gamma > 1.8$ GeV, BABAR measures energy moments of $\langle E_\gamma \rangle = (2.267 \pm 0.019_{stat} \pm 0.032_{sys} \pm 0.003_{mod})$ GeV and $(\langle (E_\gamma - \langle E_\gamma \rangle)^2 \rangle = (0.0484 \pm 0.0053_{stat} \pm 0.0077_{sys} \pm 0.0005_{mod})$ GeV^2 that are consistent with previous results [5, 6, 7]. Tagging the $B$ flavor by the lepton charge, we define the $CP$
asymmetry \( \delta_{CP}(B \rightarrow X_{s+d} \gamma) \equiv (\mathcal{N}(B \rightarrow X_{s+d} \gamma) - \mathcal{N}(B \rightarrow X_{s+d} \gamma))/\mathcal{N}(B \rightarrow X_{s+d} \gamma) \) in terms of event yields. After correcting for charge bias and mistagging, we obtain the most precise measurement of \( \delta_{CP}(B \rightarrow X_{s+d} \gamma) = 0.057 \pm 0.06_{\text{stat}} \pm 0.018_{\text{syst}} \), which is in agreement with previous results [9, 10] results and the SM prediction of zero [11].

In the semi-inclusive analysis, we combine 38 exclusive \( B \rightarrow X_s \gamma \) final states [2]. We reconstruct the hadronic mass \( m_{X_s} \) in 100 MeV/\( c^2 \) bins and calculate the photon energy by \( E_{\gamma} = \frac{m_{X_s} - m_b}{m_b} \).

Figure 1 (right) shows the partial branching fraction versus \( E_{\gamma} \). Table 1 summarizes the fit results of \( m_b \) and the kinetic energy of the \( b \) quark, \( \mu_b^2 \), extracted from fits to the kinetic scheme [12] and shape function scheme [13]. We measure energy moments of \( \langle E_{\gamma} \rangle = (2.346 \pm 0.018_{\text{stat}}^{+0.032}_{-0.022}) \) GeV and \( \langle (E_{\gamma} - \langle E_{\gamma} \rangle)^2 \rangle = (0.0211 \pm 0.0057^{+0.0055}_{-0.0060}) \) GeV\(^2\) for \( E_{\gamma} > 1.9 \) GeV. Summing the partial branching fraction over all \( m_{X_s} \) bins yields \( \mathcal{B}(B \rightarrow X_s \gamma) = (3.29 \pm 0.19_{\text{stat}} \pm 0.48_{\text{syst}}) \times 10^{-4} \) for \( E_{\gamma} > 1.9 \) GeV, which is in good agreement with the results of the inclusive analysis.

### 3. \( B \rightarrow K^{(*)} \ell^+ \ell^- \) Rates and Rate asymmetries

Using the full \( \text{BABAR} \) data sample (471 \times 10\(^6\) \( B \overline{B} \) events), we reconstructs eight \( B \rightarrow K^{(*)} \ell^+ \ell^- \) final states with \( K^\pm, K^0_s, K^\pm \pi^\pm, K^0_s \pi^\pm \) recoiling against \( e^+e^- \) or \( \mu^+\mu^- \) [14]. We suppress combinatorial \( B \overline{B} \) and \( q\overline{q} \) backgrounds with two boosted decision trees and veto the \( J/\psi \) and \( \psi(2S) \) mass regions. For \( B \rightarrow K^{(*)} \ell^+ \ell^- \) modes, we perform one- (two-) dimensional fits of the beam energy-constrained mass (and \( K\pi \) mass) to select signal yields. We use the vetoed \( J/\psi \) and \( \psi(2S) \) samples and generated pseudo experiments to check the performance of our selection.

We measure partial branching fractions \( d\mathcal{B}(B \rightarrow K^{(*)} \ell^+ \ell^-)/ds \) in six \( s = m_{\ell^+\ell^-}^2 \) bins. Figure 2 shows our results in comparison to the average over all \( d\mathcal{B}(B \rightarrow K^{(*)} \ell^+ \ell^-)/ds \) measurements from \( \text{BABAR} \) [14], Belle [15], CDF [16], and LHCb [17] and to the SM prediction[18, 19]. Table 2
Table 2: Babar results for $B \to K^{(*)}\ell^+\ell^-$ modes on total branching fractions, CP asymmetries, lepton flavor ratios, isospin asymmetries, the lepton forward-backward asymmetry and $K^*$ longitudinal polarization. The first uncertainty is statistical, the second is systematic.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}[10^{-7}]$ all s</th>
<th>$\mathcal{A}_{CP}$ all s</th>
<th>$\mathcal{A}_{K^{(*)}}$ s &gt; 0.1 GeV$^2$/c$^4$</th>
<th>$\mathcal{A}_f$ 0.1 ≤ s ≤ 8.12</th>
<th>$\mathcal{A}_{FB}$ 1.0 ≤ s ≤ 6.0</th>
<th>$\mathcal{F}_L$ 1.0 ≤ s ≤ 6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K\ell^+\ell^-$</td>
<td>4.7 ± 0.6 +0.9−1.0</td>
<td>-0.03 ± 0.14 +0.01−0.01</td>
<td>1.00 ± 0.11 +0.02−0.01</td>
<td>-0.58 ± 0.26 +0.04−0.01</td>
<td>-0.25 ± 0.17 +0.03−0.01</td>
<td>0.26 ± 0.27 +0.07−0.01</td>
</tr>
<tr>
<td>$K^*\ell^+\ell^-$</td>
<td>10.2 ± 1.4 +0.5−0.6</td>
<td>0.03 ± 0.13 +0.01−0.01</td>
<td>1.13 ± 0.34 +0.10−0.10</td>
<td>0.26 ± 0.26 +0.10−0.10</td>
<td>0.26 ± 0.26 +0.10−0.10</td>
<td>0.26 ± 0.26 +0.10−0.10</td>
</tr>
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</table>

summarizes our total branching fraction and rate asymmetry measurements. We tag the flavor of each $B$ meson to determine the CP asymmetry

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(B \to K^{(*)}\ell^+\ell^-) - \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)}{\mathcal{B}(B \to K^{(*)}\ell^+\ell^-) + \mathcal{B}(B \to K^{(*)}\ell^+\ell^-)}$$

that is expected to be very small in the SM [20, 21]. We extract the lepton flavor ratios

$$\mathcal{R}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

with the constraint s > 0.1 GeV$^2$/c$^4$ yielding the SM prediction $R_{K^{(*)}} = 1$ [22]. Accounting for the different $B$ lifetimes $r = \frac{s}{\Delta s}$, we define the isospin asymmetry

$$d\mathcal{A}_f/ds = \frac{d\mathcal{B}(B^0 \to K^{(*)}0\ell^+\ell^-)/ds - r d\mathcal{B}(B^{\pm} \to K^{(*)}\pm\ell^+\ell^-)/ds}{d\mathcal{B}(B^0 \to K^{(*)}0\ell^+\ell^-)/ds + r d\mathcal{B}(B^{\pm} \to K^{(*)}\pm\ell^+\ell^-)/ds}.$$ 

Figure 2: d$\mathcal{B}$/ds for $B \to K\ell^+\ell^-$ (left) and $B \to K^*\ell^+\ell^-$ (right) for Babar data (squares), the experimental average (points) and the SM prediction (grey curves). Vertical bands show the $J/\psi$ and $\psi(2S)$ vetoes.

Figure 3 shows the isospin asymmetry for $B \to K^{(*)}\ell^+\ell^-$ modes in six s bins in comparison to the average over all experiments [14, 15, 16, 17]. In the SM, $\mathcal{A}_f$ is expected to be of the order of $\mathcal{O}(1\%)$ [23]. The $\mathcal{A}_f$ measurements below the $J/\psi$ are listed in Table 2. For $B \to K\ell^+\ell^-$, consistency with the SM is at the 2.1σ level. All other measurements of branching fractions, CP asymmetries and lepton flavor ratios are in good agreement with the SM prediction [7, 8, 18, 19].

4. $B \to K^{(*)}\ell^+\ell^-$ Angular Analyses

The $B \to K^{(*)}\ell^+\ell^-$ decay is characterized by three angles: $\theta_K$ the angle between the $K$ and $B$ in the $K^*$ rest frame, $\theta_\ell$ the angle between the $\ell^+$ and the $B$ in the $\ell^+\ell^-$ rest frame and $\phi$ the angle
between the $K^*$ and $\ell^+\ell^-$ decay planes. The one-dimensional $\cos \theta_K$ and $\cos \theta_\ell$ distributions depend on the $K^*$ longitudinal polarization $F_L$ and the lepton forward-backward asymmetry $A_{FB}$ [22, 24]

$$W(\cos \theta_K) = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) \sin^2 \theta_K;$$

$$W(\cos \theta_\ell) = \frac{3}{4} F_L \sin^2 \theta_\ell + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell. \quad (4.1)$$

Using the full BABAR data sample, we reconstructs six $B \to K^* \ell^+\ell^-$ final states with $K^* \to K^\pm \pi^\mp, K^0_L \pi^\pm, K^\pm \pi^0$. The event selection is similar to that for rate asymmetries. We extract $F_L$ and $A_{FB}$ by performing a profile likelihood scan. Figure 4 shows our $F_L$ and $A_{FB}$ measurements in six $s$ bins in comparison to the average over all experiments, the SM predictions with uncertainties and predictions for a model in which the sign of Wilson coefficient $C_7^{eff}$ is flipped with respect to the expected SM value [22, 20]. All results are consistent with the SM prediction. In the low $s$ region ($1 < s < 6 \text{ GeV}^2/c^4$), the BABAR results are listed in Table 2. They are consistent with the SM predictions of $F_L^{SM} = 0.73^{+0.13}_{-0.23}$ and $A_{FB}^{SM} = -0.05^{+0.03}_{-0.04}$ [18, 20, 22, 25] and with the world averages of $F_L^{WA} = 0.41 \pm 0.06$ and $A_{FB}^{WA} = 0.11^{+0.08}_{-0.09}$ [4].

**Figure 3:** Isospin asymmetry for $B \to K\ell^+\ell^-$ (left) and $B \to K^*\ell^+\ell^-$ (right) for BABAR data (squares) and the experimental average (points). Vertical bands show the $J/\psi$ and $\psi(2S)$ vetoes.

**Figure 4:** BABAR preliminary results (squares) for $A_{FB}$ (left) and $F_L$ (right) for $B \to K^*\ell^+\ell^-$ modes compared to the average over all experiments (points), the SM prediction (shaded curves) and a model for which the sign of $C_7^{eff}$ is flipped (blue curve). Vertical bands show the $J/\psi$ and $\psi(2S)$ vetoes.
5. Conclusion

The **B** → **X s γ** results on branching fractions, photon energy moments, \(m_h\), \(\mu^2\) and the \(CP\) asymmetry are in good agreement with the SM predictions. The charged Higgs mass is constrained to \(M_H > 327 \text{ GeV}^2/c^2\) at 95% CL independent of \(\tan \beta\). For \(B \rightarrow K^{(*)}\ell^+\ell^-\), the **B**AR results on partial branching fraction, isospin asymmetries, lepton flavor ratios, \(CP\) asymmetries, \(K^*\) longitudinal polarization, and lepton forward-backward asymmetry are consistent with the SM predictions. Significant improvement on these measurements will come from LHCb and the Super **B**-factories. The large data samples will permit to study several new angular observables that provide higher discrimination power between the SM and new physics effects.

References