Review of $b \to s\ell^+\ell^-$ and $B^0 \to \ell^+\ell^-$ Decays

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Latest experimental results on flavor-changing neutral current $B$ meson decays involving di-lepton are reviewed. This review covers exclusive $B \to K^{(*)}\ell^+\ell^-$, inclusive $B \to X_s\ell^+\ell^-$ and $B^0 \to \ell^+\ell^-$.  

1 Introduction

In the Standard Model (SM), flavor-changing neutral current (FCNC) decays are forbidden at tree level. However, FCNC decays are induced through loop diagrams, such as penguin diagrams or box diagrams. These loop diagrams are sensitive to new physics, since heavy particles beyond the SM, such as charged Higgs or SUSY particles, can contribute to additional loop diagrams and thereby modify the branching fraction or kinematic variables. This feature makes FCNC processes an ideal place to search for new physics.

2 $b \to s\ell^+\ell^-$ Decays

The branching fraction of $b \to s\ell^+\ell^-$ decays are described in term of the Wilson coefficients $C_7$, $C_9$ and $C_{10}$. These coefficients are cleanly predicted in the SM, thus the deviation from the SM can be translated as new physics effect.

The magnitude of $C_7$ is strongly constrained by the measurements of branching fraction of inclusive $B \to X_s\ell^+\ell^-$ [1, 2, 3]. However sign of $C_7$ have not determined yet and $C_9$ and $C_{10}$ was poorly known before Belle had observed the $K\ell^+\ell^-$ [4].

Experimentally, exclusive $K^{(*)}\ell^+\ell^-$ decays are easier to analyze than inclusive $B \to X_s\ell^+\ell^-$. However exclusive decays suffer large theoretical uncertainty due to form factor, while inclusive decay is theoretically clean.

2.1 Measurements of $B \to K^{(*)}\ell^+\ell^-$

$B \to K^{(*)}\ell^+\ell^-$ decays were searched by Belle, Babar, CLEO and CDF [5, 6, 7, 8]. The analysis techniques were different between $e^+e^-$ B-factory experiments (Belle, Babar and CLEO) and CDF. The $e^+e^-$ B-factory experiments reconstructed eight decay modes: charged and neutral $B$ decay to $Ke^+e^-$, $K\mu^+\mu^-$, $K^*e^+e^-$ and $K^*\mu^+\mu^-$. Continuum background was reduced by a Fisher discriminant based on event shape parameters. $B\overline{B}$ background was suppressed by missing energy and $B$ meson momentum direction. The signal events were selected using two variables: the beam energy constrained mass $M_{bc}$ and the energy difference $\Delta E$. While
CDF only searched for muon modes. Backgrounds were suppressed by track isolation, impact parameter and vertex quality. The signal events were selected using $B$ meson mass. All experiments vetoed the backgrounds from $J/\psi$ and $\psi'$ by dilepton invariant mass cut.

Figs 1 show the $M_{bc}$ distributions by Belle with 60 fb$^{-1}$ data and Babar with 78 fb$^{-1}$ data. Both Belle and Babar observed a clear $K\ell^+\ell^-$ signal. While $K^*\ell^+\ell^-$ was not significant. In calculating the combined branching fractions, isospin symmetry, lepton universality and equal fraction of charged and neutral $B$ meson production were assumed. However $K^*\ell^+\ell^-$ has a photon pole at $q^2 = 0$, thus the branching fraction is different between $K^*e^+e^-$ and $K^*\mu^+\mu^-$. Belle assumed the ratio of branching fraction of $K^*e^+e^-$ to $K^*\mu^+\mu^-$ to be 1.33 [9] and took an average of two modes, while Babar used 1.21 [10] and scaled the combined branching fraction to electron mode. Branching fractions and upper limits are summarized in Table 1. Belle and Babar combined branching fraction $B(B \to K\ell^+\ell^-)$ = (0.63$^{+0.17}_{-0.15}$)$ \times 10^{-6}$ is consistent with the SM prediction and the error is already comparable to the theoretical error.

<table>
<thead>
<tr>
<th>BF ($\times 10^{-6}$)</th>
<th>$B \to K\ell^+\ell^-$</th>
<th>$B \to K^*\ell^+\ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>$0.58^{+0.11}_{-0.16} \pm 0.06$</td>
<td>$&lt; 1.4$</td>
</tr>
<tr>
<td>Babar</td>
<td>$0.78^{+0.24+0.11}_{-0.20-0.18}$</td>
<td>$&lt; 3.0$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$&lt;1.7$</td>
<td>$&lt;3.3$</td>
</tr>
<tr>
<td>CDF</td>
<td>$&lt;5.2$</td>
<td>$&lt;4.0$</td>
</tr>
</tbody>
</table>

Table 1: The branching fractions and upper limits for $B \to K^{(*)}\ell^+\ell^-$

Figure 1: The $M_{bc}$ distributions with fits for $B \to K^{(*)}\ell^+\ell^-$ by Belle (left) and Babar (right).
2.2 A First Measurement of $B \to X_s \ell^+ \ell^-$

Belle had performed a first measurement of $B \to X_s \ell^+ \ell^-$ with 60 fb$^{-1}$ data [11]. The $X_s$ system was reconstructed from either $K^+$ or $K^0_S$ combined with 0 to 4 pions, of which up to one neutral pion is allowed. This set of combination covers $(81 \pm 2)\%$ of the total inclusive decays based on a model discusses below.

To optimize the selection criteria and determine the signal efficiency, the Monte Carlo simulation used theoretical models as input for the dilepton mass spectrum [9] and the hadronic mass spectrum [12]. The hadronic system was produced according to JETSET. For $M_{X_s}$ less than 1.1 GeV/$c^2$, the exclusive $B \to K^{(*)} \ell^+ \ell^-$ were used based on the model of Ali et al. [9]. To remove the photon pole in electron mode, dilepton invariant mass was required to be greater than 200 MeV/$c^2$. This makes predicted branching fraction for the electron mode and muon mode approximately equal; $\mathcal{B}(B \to X_s e^+ e^-) \sim \mathcal{B}(B \to X_s \mu^+ \mu^-) = (4.2 \pm 0.7) \times 10^{-6}$.

Analysis procedure is almost same as exclusive one. Continuum background was suppressed by a Fisher discriminant based on event shape parameters. $B\overline{B}$ background was reduced by a Fisher discriminant based on missing energy and missing mass. When multiple candidates were found in an event, the largest value of likelihood, which is formed based on energy difference and cosine of the $B$ candidate flight direction with respect to the $e^+$ beam direction in the c.m. frame, was selected. The backgrounds from $J/\psi$ and $\psi'$ were vetoed by dilepton invariant mass. The veto windows are much wider than that in exclusive analysis since the $J/\psi$ events whose dilepton invariant mass evade from the veto window can be background by adding pions from the other $B$ decay. The candidates with invariant mass of hadronic system greater than 2.1 GeV/$c^2$ were rejected. This condition removes a large fractions of combinatrial background while retaining $(93 \pm 5)\%$ signal events. The signal events were selected from fit to the $M_{bc}$.

Figure 2.2 shows the results of $M_{bc}$ fit. We can see a clear peak in both $X_s e^+ e^-$ and $X_s \mu^+ \mu^-$. Belle found 60.1 ± 13.9 signal events in the combined $X_s \ell^+ \ell^-$ mode with a significance of 5.4. The branching fraction obtained is $(6.1 \pm 1.4^{+1.3}_{-1.5}) \times 10^{-6}$. The systematic error was already comparable to statistical error. Largest source was uncertainty in exclusive fractions(∼ 11%). This could be reduce by using measured branching fractions. Second largest was track finding, which could be reduced by half. Table 2 summarizes the branching fraction measured by Belle together with CLEO’s search results [13].

Figure 3 shows a comparison between experiments and theories. The measured branching fractions are consistent with the theoretical predictions, so far.

<table>
<thead>
<tr>
<th>BF ($\times 10^{-6}$)</th>
<th>$B \to X_s e^+ e^-$</th>
<th>$B \to X_s \mu^+ \mu^-$</th>
<th>$B \to X_s \ell^+ \ell^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>$5.0 \pm 2.3^{+1.3}_{-1.1}$</td>
<td>$7.9 \pm 2.1^{+2.1}_{-1.5}$</td>
<td>$6.1 \pm 1.4^{+1.4}_{-1.5}$</td>
</tr>
<tr>
<td>CLEO</td>
<td>&lt; 57</td>
<td>&lt; 58</td>
<td>&lt; 42</td>
</tr>
</tbody>
</table>

Table 2: The branching fractions and upper limits for $B \to X_s \ell^+ \ell^-$

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Figure 2: The $M_{bc}$ distributions with fits for $B \to X_s \ell^+ \ell^-$ by Belle.

Figure 3: Comparison between experimental results and theoretical predictions.
2.3 Constraint on $C_9$ and $C_{10}$

The Wilson coefficients $C_9$ and $C_{10}$ can be constrained from measured branching fractions of $B \to K\ell^+\ell^-$ and $B \to X_s\ell^+\ell^-$. Figure 4 shows allowed region in $C_9$-$C_{10}$ plane for $C_7$ negative (left) case and positive (right) case [14]. A large area had been excluded, though the sign of $C_7$ had not been determined yet.

![Figure 4: Allowed region in $C_9$-$C_{10}$ plane. Left is $C_7$ negative case and right is $C_7$ positive case.](image)

3 Searched for $B^0 \to \ell^+\ell^-$

$B^0 \to \ell^+\ell^-$ decays are very rare since it proceeds through higher order diagrams, such as penguin annihilation or box diagrams, and is suppressed due to helicity flip. The branching fraction predicted in the SM is $O(10^{-15})$ for $B^0 \to e^+e^-$ and $O(10^{-10})$ for $B^0 \to \mu^+\mu^-$. However new physics can enhances the branching fraction by 2 to 3 order of magnitude larger. The $B^0 \to e^\pm\mu^\mp$ is forbidden in the SM by lepton flavor conservation. However this decay can occur via Pati-Salam leptoquark [15].

Babar, CLEO and CDF searched for $B^0 \to \ell^+\ell^-$ decay [16, 17, 18, 19] and Belle showed new results on the decay. At the $e^+e^-$ B-factories, continuum is the dominant background source to the decay modes. A tight continuum suppression based on event shape was applied. The signal events were selected from the $M_{bc}$ and the $\Delta E$. At CDF, the background is suppressed by track isolation, impact parameter and vertex quality. The signal event was selected using $B$ meson mass.

Figs 5 show the $M_{bc}$ vs $\Delta E$ by Belle and Babar. Both experiments observed no event in $B^0 \to \mu^+\mu^-$ and $B^0 \to e^\pm\mu^\mp$ while observed one event in $B^0 \to e^+e^-$ which is consistent with
background. The upper limits obtained by Belle and Babar are almost one order of magnitude better than those by CLEO. The 90\% CL upper limits on the branching fractions were obtained from the results and summarized in Table 3. The limit on the branching fraction of $B^0 \rightarrow e^\pm \mu^\mp$ can be translated as the lower limit on the mass of the Pati-Salam leptoquark. Belle gave the most stringent limits $M_{LQ} > 54$ TeV/$c^2$.

<table>
<thead>
<tr>
<th>Limit ($\times 10^{-8}$)</th>
<th>$B(B^0 \rightarrow e^+e^-)$</th>
<th>$B(B^0 \rightarrow \mu^+\mu^-)$</th>
<th>$B(B^0 \rightarrow e^\pm \mu^\mp)$</th>
<th>$M_{LQ}$ (TeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>&lt; 20</td>
<td>&lt; 8.3</td>
<td>&lt; 9.1</td>
<td>&gt; 54</td>
</tr>
<tr>
<td>Babar</td>
<td>&lt; 33</td>
<td>&lt; 20</td>
<td>&lt; 21</td>
<td>-</td>
</tr>
<tr>
<td>CLEO</td>
<td>&lt; 830</td>
<td>&lt; 61</td>
<td>&lt; 150</td>
<td>&gt; 27</td>
</tr>
<tr>
<td>CDF</td>
<td>-</td>
<td>&lt; 86</td>
<td>&lt; 350</td>
<td>&gt; 22</td>
</tr>
</tbody>
</table>

Table 3: Upper limits for the branching fractions of $B^0 \rightarrow \ell^+\ell^-$ decays and lower limit for the Pati-Salam leptoquark.

Figure 5: $M_{bc}$ vs $\Delta E$ for $B \rightarrow \ell^+\ell^-$ decays by Belle (upper) and Babar (lower).
4 Conclusions

Rare $B$ decays involving leptons have the potential to search for the new physics beyond the SM. The measurements of $B \rightarrow K\ell^+\ell^-$ and inclusive $B \rightarrow X_s\ell^+\ell^-$ already exclude the large parameter space in the new physics. Searches for $B \rightarrow \ell^+\ell^-$ by Belle and Babar gave about one order improvement on the upper limits of branching fractions.

Belle, Babar, CDF and D0 will give the precise measurement or stringent limits with coming data.

References
