Belle Results on $b \to s\ell^+\ell^-$ and $b \to \gamma$

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We discuss the latest results and future prospects of the Belle experiment on the electroweak and radiative processes $b \to s\ell^+\ell^-$ and $b \to \gamma$ in which two leptons are either from two charm decays. The continuum background is smaller than semileptonic decays. These backgrounds do not produce signal peaks, and the background rate is large. The $\ell$ process has been a powerful tool to constrain physics beyond the Standard Model (SM). The radiated photon serves as a probe to study short distance loop diagrams through a comparison of the decay rate with theory calculations and through a search for direct CP asymmetry. In addition, the radiated photon also probes the kinematical property of decays through the photon energy spectrum, which is useful to constrain the lepton spectrum in $|V_{ub}|$ measurements.

A similar process, $b \to s\ell^+\ell^-$ ($\ell = e, \mu$), acts as an additional probe for new physics, since the existence of the $Z$-boson radiation and $W$-boson box diagrams may enhance the effects from new physics. The rate is about two orders of magnitude smaller than $b \to s\ell^+\ell^-$, but with the signal two energetic leptons is very clean. The lepton pair in the final state provides two additional observables that can be used to identify new physics effects: the differential branching fraction and the lepton forward-backward asymmetry, as functions of the dilepton mass. Recently Belle observed the first $B \to K\ell^+\ell^-$ events, and successfully measured the inclusive branching fraction for $B \to X_s\ell^+\ell^-$. Another process, $b \to d\gamma$, is also suppressed by two orders of magnitude with respect to $b \to s\gamma$, naively due to the CKM factor $|V_{ub}/V_{ts}|^2$. Although the rate is similar to $b \to s\ell^+\ell^-$, the signal is less clean due to huge backgrounds of $b \to s\gamma$ and energetic $\pi^0 \to \gamma\gamma$ from the continuum $q\bar{q}$ ($q = u, d, s, c$) production. Assuming that the non-SM contributions to $b \to s\gamma$ and $b \to d\gamma$ are small, we can constrain the value of $|V_{ub}/V_{ts}|^2$ from a $b \to d\gamma$ measurement. It is very important to compare the $|V_{ub}/V_{ts}|$ value from $b \to d\gamma$ with those from the $B_d^0 \to B_d^0$ mixing, since the latter involves lattice QCD calculations and may be affected by new physics that appear only in the mixing diagram.

In this report, we summarize the latest Belle results on the electroweak and radiative $B$ decays, and discuss the future prospects. We anticipate that a large dataset of 500 fb$^{-1}$ will be ready within the next two to three years of KEKB/Belle operation.
sive branching fraction

\[ \mathcal{B}(B \to X_c \ell^+ \ell^-) = (6.1 \pm 1.4^{+1.3}_{-1.1}) \times 10^{-6} \]  

(1)

with a kinematical cut of \( M(\ell^+ \ell^-) > 0.2 \) GeV/\( c^2 \); for all the other cuts, the branching fraction is extrapolated to the entire phase space. By subdividing the sample into bins, we measure the \( M(\ell^+ \ell^-) \) and \( M(X_c) \) distributions as shown in Fig. 1 with a comparison to the SM expectations. The measured inclusive branching fraction can be compared with the SM prediction of \((4.2 \pm 0.7) \times 10^{-6}\). The result is in agreement with the SM; however, the measurement error is still too large to be conclusive.

We also performed a separate analysis for the exclusive \( B \to K^{(*)}\ell^+\ell^- \) modes with the same 60 fb\(^{-1}\) dataset [3]. We increased the precision of the \( B \to K\ell^+\ell^- \) result, but no significant signal was observed for \( B \to K^{*}\ell^+\ell^- \) for which we quote a 90% confidence level upper limit. The updated results are

\[ \mathcal{B}(B \to K\ell^+\ell^-) = (5.8^{+1.7}_{-1.5} \pm 0.6) \times 10^{-7} \]
\[ \mathcal{B}(B \to K^{*}\ell^+\ell^-) < 14 \times 10^{-7}. \]  

(2)

The number of events in the inclusive measurement indicates that the first measurement of the forward-backward asymmetry will be feasible in near future using the pseudo-reconstruction samples, even after excluding the \( B \to K\ell^+\ell^- \) contribution which does not produce an asymmetry. The exclusive \( B \to K^{*}\ell^+\ell^- \) mode is also expected to be observed soon, and a forward-backward asymmetry measurement using the exclusive sample will be complementary.

3 \( b \to s \gamma \) processes

The exclusive radiative decay \( B \to K^{\prime}\gamma \) provides one of the most precise measurements among \( B \) meson rare decays. Signal is clearly seen as shown in Fig. 2 separately for each \( K^{\prime} \) final state and charge. We measured the \( B \to K^{\prime}\gamma \) branching fractions and CP asymmetry using a 60 fb\(^{-1}\) dataset [4]

\[ \mathcal{B}(B^0 \to K^{0}\gamma) = (39.1 \pm 2.3 \pm 2.5) \times 10^{-6} \]
\[ \mathcal{B}(B^+ \to K^{*+}\gamma) = (42.1 \pm 3.5 \pm 3.1) \times 10^{-6} \]
\[ A_{CP}(B \to K^{\prime}\gamma) = (-2.2 \pm 4.8 \pm 1.7) \times 10^{-2}. \]  

(3)

The branching fraction may be compared with the SM prediction, for example, \((7 \pm 2) \times 10^{-5} \) [5]. The predicted branching fraction is higher than the measured value, but one cannot consider this seriously due to large model-dependent form factor uncertainties in the prediction. We also note that the branching fraction for the neutral and charged decays are about the same size, and are not yet sensitive to the isospin asymmetry proposed in ref. [6].

![Figure 1](image1.png)  
**Figure 1.** Dilepton and recoil mass spectrum in the \( B \to X_c \ell^+\ell^- \). Upper plots shows a SM model, and lower plots show the measurements (data points) compared with the efficiency corrected predictions (histograms).

![Figure 2](image2.png)  
**Figure 2.** Beam constrained mass spectrum for \( B \to K^{\prime}\gamma \), separately shown for charge conjugated samples.
window of $\pm 150$ (30) MeV/$c^2$ around the nominal mass. About a half of the $K^*$ with a pion mass hypothesis for the kaon falls into this $\rho$ mass window. The $K^\gamma$ background is much more severe in the neutral mode, since the sub-decay branching fraction of $K^0 \to K^\pi^-$ is twice as high as that of $K^{*+} \to K^\pi^0$ and the expected branching fraction for $B^0 \to \rho^0\gamma$ is twice as low as that for $B^{+} \to \rho^+\gamma$. Therefore, we explicitly reject the events if the $K^+\pi^-$ invariant mass (with a kaon mass hypothesis for one of the pions) is in a range of $\pm 50$ MeV/$c^2$ of the $K^*$ mass.

Using a 78 fb$^{-1}$ dataset, we performed a simultaneous fit to the three modes of $\rho^+\gamma$, $\rho^0\gamma$ and $\omega\gamma$ (we denote as $(\rho + \omega)\gamma$ with an assumption of the isospin relation $\Gamma(\rho + \omega)\gamma) = \Gamma(\rho^\pm\gamma) = 2\Gamma(\rho^0\gamma) = 2\Gamma(\omega\gamma)$. In this case, we neglect isospin violating effects such as the annihilation diagram contribution that only appears in $B \to \rho^+\gamma$. We also perform a simultaneous fit to the three $(\rho + \omega)\gamma$ modes and two $K^\gamma\gamma$ modes to evaluate the ratio $\Gamma(B \to (\rho + \omega)\gamma)/\Gamma(B \to K^\gamma\gamma)$. For this updated analysis, we re-optimized the signal yield extraction method from the previous analysis with 60 fb$^{-1}$ [3]. We decided to use a fit to the distribution of the energy difference ($\Delta E$), from a toy Monte Carlo study to optimize the result of the ratio. After selecting the events in the $2\sigma$ window of $M_{bc}$ and optimizing the continuum suppression cut, which is based on a likelihood ratio of the $B$ meson flight direction and a Fisher discriminant formed from a modified set of Fox-Wolfram moments, we fit the $\Delta E$ distribution with a linear continuum background component, a MC determined $B$ decay background component and two Crystal Ball line shapes to represent the signal and the $K^\gamma\gamma$ component (not in the $\omega\gamma$ mode). The $\Delta E$ peak is shifted by $-60$ MeV for the $K^\gamma\gamma$ background. The individual fit result for each mode is shown in Fig. 4.

We observe no significant signal yield in the individual fits nor in the simultaneous fits, and obtain the following 90% confidence level upper limits

$$
\begin{align*}
B(B^0 \to K_2^*(1430)^0\gamma) &< 2.7 \times 10^{-6} \\
B(B^0 \to K^\pi^+\pi^-\gamma) &< 2.6 \times 10^{-6} \\
B(B^0 \to \omega\gamma) &< 4.4 \times 10^{-6} \\
B(B \to (\rho + \omega)\gamma) &< 3.0 \times 10^{-6} \\
\Gamma(B \to (\rho + \omega)\gamma)/\Gamma(B \to K^\gamma\gamma) &< 0.081.
\end{align*}
$$

These results are still a few times larger than the SM predictions, and the ratio does not give a useful constraint on $|V_{ub}/V_{cb}|$ yet.

From the current analysis, one can estimate how much sensitivity we expect on the search for the $B \to (\rho + \omega)\gamma$ signal. In Fig. 5, we use the efficiency and the size of the backgrounds in the current analysis to extrapolate the sensitivity for the first observation of the $B \to (\rho + \omega)\gamma$ signal. It is seen that we need 250 to 500 fb$^{-1}$ of data if the branching fraction is 1 to $1.5 \times 10^{-6}$ as predicted.

4 $B \to d\gamma$ processes

The $B \to d\gamma$ process is expected to be observed in one of the exclusive modes, $B \to \rho\gamma$ and $B \to \omega\gamma$. The analysis is similar to the study of $B \to K^\gamma\gamma$. Since the expected branching fraction is almost two orders of magnitude smaller than $B \to K^\gamma\gamma$, continuum background is very high. $B \to K^\gamma\gamma$ is also a significant background, since the particle identification, which is mainly based on the threshold aerogel Cherenkov detector, has almost 10% kaon to pion fake rate. Candidate $\rho$ ($\omega$) mesons are selected in a
Once the first branching fraction measurement is made, there will be a 20 to 30\% experimental error. One has to assume a rather large theory error on the form factor ratio between $B \to (\rho + \omega)$ and $B \to K^*$ to interpret the result in terms of $|V_{td}/V_{ts}|$. At this moment, there is no well defined idea to shrink the theory error.

Another possibility is to aim for an inclusive measurement of theoretically cleaner $B \to X_d \gamma$. However, no clear idea is known how one can control the enormous $B \to X_s \gamma$ backgrounds, and this may not be a possible project in the coming few years.

### 5 Conclusion

The long awaited first inclusive measurement of $B \to X_d \ell^+ \ell^-$ was performed by Belle. Although the results are consistent with the SM, the error is still large. The results also demonstrate that future programs such as the measurement of the forward backward asymmetry are feasible by adding more data.

Exclusive measurements of $b \to s \gamma$ processes have been extensively carried out by Belle. These results become important to understand the properties of the hadron recoil system in the next $B \to X_d \gamma$ measurement, in which we expect a better understanding of systematic errors.

The $b \to d \gamma$ process has not been measured yet, but with the dataset of about 500 fb$^{-1}$, anticipated in the next few years, it is likely to have the first measurement of the exclusive process $B \to (\rho + \omega) \gamma$. This will be important to constrain the value of $|V_{td}/V_{ts}|$ without relying on $B^0_{d,s} \bar{T}^0_{d,s}$ mixing and lattice calculations.

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