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RARE B DECAYS

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ABSTRACT

Recent results from Belle and BaBar on rare B decays involving flavour-changing neutral currents or purely leptonic final states are presented. Measurements of the CP asymmetries in $B \to K^*\gamma$ and $b \to s\gamma$ are reported. Also reported are updated limits on $B^+ \to K^+\nu\bar{\nu}$, $B^+ \to \tau^+\nu$, $B^+ \to \mu^+\nu$ and the recent measurement of $B \to X_s\ell^+\ell^-$.

1 Introduction

The study of radiative and leptonic rare B decays represents a very attractive field in the search for discrepancies with respect to the theoretical predictions of the Standard Model (SM). Many extensions to the Standard Model predict visible effects in these decays whose measurements allow constraints to be placed on new physics, or indeed, the potential to discover such phenomena. The BaBar [1)] and Belle [2)] collaborations are exploiting the unprecedented

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luminosities provided by the PEP-II and KEK-B facilities to perform an extensive and detailed series of studies of these decay channels. Samples on the order of 200×10^6 $\Upsilon(4S)\to B\bar{B}$ decays have been recorded by the two collaborations. The paper will summarise experimental results based on a subset of these datasets.

2 Electroweak penguin decays

In the SM, the amplitudes which contribute to the $b\to s\ell^+\ell^-$ and the $b\to s\nu\bar{\nu}$ decays at leading order are the W^+W^- box diagram, the Z^0 penguin diagram and, for the charged lepton decay, the photonic penguin diagram. An important consequence of the loop structure of these decays is that their branching fractions and their kinematic variables, such as the transferred momentum squared or the virtual γ or Z ($q^2 = M(\ell^+\ell^-)^2$) and the forward-backward asymmetry of the lepton decay angle (A_{FB}) in the $b\to s\ell^+\ell^-$ decays, can be significantly affected by the presence of new particles or couplings predicted in non-standard scenarios.

2.1 $B\to X_s\ell^+\ell^-$

The BaBar collaboration finalised measurements of branching fractions of the exclusive processes $B\to K\ell^+\ell^-$ and $B\to K^*\ell^+\ell^-$ [3] using 113fb^{-1} of data. A preliminary measurement of the inclusive branching fraction $B\to X_s\ell^+\ell^-$ using a sum over exclusive modes in which X_s system is composed of one charged kaon and one or more charged and/or neutral pions [4] yielding:

$$B(B\to X_s\ell^+\ell^-) = (6.3\pm1.6^{+1.8}_{-2.5})\times10^{-6}. \qquad (1)$$

All of these results are consistent with the SM theoretical predictions.

2.2 $B^+\to K^+\nu\bar{\nu}$

The $B^+\to K^+\nu\bar{\nu}$ measurement is experimentally challenging due to the presence of two unobserved neutrinos in the final state. BaBar has performed a search for this decay using 88×10^6 $B\bar{B}$ pairs using two techniques: Where one B in the event is reconstructed hadronically, $B^-\to D^0X_{\mathrm{had}}$, or where the B is reconstructed semileptonically, $B^-\to D^0\ell^-\bar{\nu}X$. The system recoiling against this reconstructed meson is considered for consistency with the $B^+\to K^+\nu\bar{\nu}$ signal. Candidate events are required to contain one charged kaon with CM momentum greater than 1.5 GeV/c and less than 250 MeV of additional neutral energy, E_{extra}, measured in the calorimeter.

Combining the two statistically independent analyses yields an upper limit on the branching fraction at the 90% confidence level of:

$$B(B^+ \to K^+ \nu\bar{\nu}) < 7.0 \times 10^{-5}, \tag{2}$$

which represents the best upper limit on this channel. This analysis is similar to that discussed in section 5.1.

3 Radiative B decays

Radiative decays, such as $b \to s\gamma$, proceed at leading order in the SM through one loop penguin diagrams. The new fields predicted by many extensions to the SM can contribute with additional amplitudes to this process appearing as virtual particles in the penguin loop diagrams. A comparison of the measured inclusive branching ratio (world average $B(B \to X_s\gamma) = 3.3 \times 10^{-4}$ [5]) with respect to the SM theorectical predictions ($(3.6\pm0.3)\times10^{-4}$ [6, 7]) has already provided some constraint on the new physics beyond the SM [8].

3.1 $b \to s\gamma$

Using a sample of 152×10^6 $B\bar{B}$ decays Belle recently measured the $b \to s\gamma$ branching fraction using a fully-inclusive approach. A detailed description of the analysis can be found elsewhere. In this analysis the $b \to s\gamma$ signal spectrum was extracted by collecting all high-energy photons, vetoing those from π^0 and η decays to two photons. The contribution from continuum events was subtracted using the off-resonance data sample. The remaining backgrounds from $B\bar{B}$ events are subtracted using Monte Carlo (MC) distributions scaled by data control samples. After subtracting the backgrounds the photon energy spectrum is corrected for the signal selection efficiency function obtained from signal MC after applying the correction determined by data control samples.

The efficiency-corrected spectrum is shown as a function of CM photon energy in Figure 1. The two error bars for each point show the statistical and the total error, including the systematic error which is correlated among the points. As expected, the spectrum above the 3 GeV endpoint for decays of B mesons from the $\Upsilon(4S)$ is consistent with zero. Integrating this spectrum from 1.8 to 2.8 GeV a partial branching fraction is obtained of $B(b \to s\gamma) = (3.59 \pm 0.32^{+0.30}_{-0.31}\ ^{+0.11}_{-0.07}) \times 10^{-4}$, where the errors are statistical, systematic and theoretical respectively. This result is in good agreement with the latest theoretical calculations [9]. The moments of the distribution are also measured yielding $\langle E_\gamma \rangle = 2.289\pm0.026\pm0.034$ GeV and $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2 = 0.0311\pm0.0073\pm$

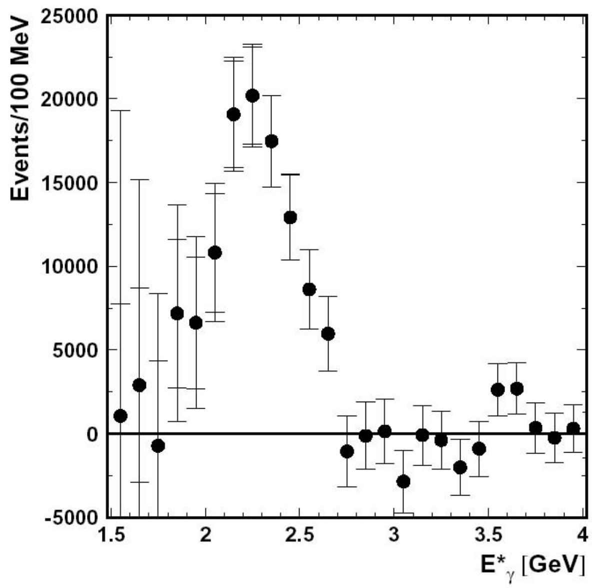

Figure 1: *Efficiency-corrected photon energy spectrum. The two error bars show the statistical and total errors.*

0.0063 GeV^2 for $E^*_\gamma > 1.8$ GeV, where the errors are statistical and systematic respectively.

3.2 $b \to d\gamma$

The $b \to d\gamma$ process is suppressed with respect to $b \to s\gamma$ by the Cabibbo-Kobayashi-Maskawa (CKM) factor $|V_{td}/V_{ts}|^2$ with a large uncertainty due to the lack of precise knowledge on V_{td}.

In the analysis performed by the Belle collaboration (using the same sample as the $b \to s\gamma$ analysis reported in the previous section) the exclusive reconstruction of the decays $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$ and $B \to \omega\gamma$ is performed. $B^+ \to K^{*+}\gamma$ and $B^0 \to K^{*0}\gamma$ are reconstructed as control samples. The folowing decay chains are used to reconstruct the intermediate states: $\rho^+ \to \pi^+\pi^0$, $\rho^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$, $K^{*+} \to K^+\pi^0$ $K{*}0 \to K^+\pi^-$ and $\pi^0 \to \gamma\gamma$. In each event a photon with the largest energy in the range 1.8 GeV $< E_\gamma <$ 3.4 GeV is selected in the e^+e^- center-of-mass frame (CM). Vetoes are applied to suppress backgrounds from π^0 and η decays to pairs of photons. B candidates are formed by combining a ρ or ω candidate and the primary photon using two variables: the beam-energy constrained mass $M_{bc} = \sqrt{(E^*_{\rm beam}/c^2)^2 - |p^*_B/c|^2}$ and the energy difference $\Delta E = E^*_B - E^*_{\rm beam}$, where

p_B^* and E_B^* are the measured CM momentum and energy, respectively, of the B candidate, and $E^*_{\rm beam}$ is the CM beam energy. The photon energy is replaced by $E^*_{\rm beam} - E^*_{\rho/\omega}$, if the momentum p_B^* is calculated. The signal region is defined as -0.1 GeV $< \Delta E < 0.08$ GeV and 5.273 GeV/c$^2 < M_{bc} < 5.285$ GeV/c^2.

There are two major sources of background from B decays: $B \to K^*\gamma$ and $B \to \rho/\omega\pi^0$. To suppress $B \to K^*\gamma$, we calculate $M_{K\pi}$, where the kaon mass is assigned to one of the pion candidates, and reject the candidate if $M_{K\pi} < 0.96(0.92)$ GeV/c^2 for the $\rho^0\gamma(\rho^+\gamma)$ mode. to reject $B \to \rho/\omega\pi^0$, a helicity angle cut is applied such that $|\cos\theta_{\rm hel}| > 0.8(0.6)$ for $\rho^0\gamma$ and $\omega\gamma(\rho^+\gamma)$ modes. Here, $\theta_{\rm hel}$ is the angle between the π^+ and B momentum vectors in the ρ rest frame or between the normal to the ω decay plane and the B momentum vector in the ω rest frame.

The background from continuum $e^+e^- \to q\bar{q}(q = u, d, s, c)$ events is rejected using event topology information. A Fisher [10] discriminant is constructed from 16 modified Fox-Wolfram [11] moments and the scalar sum of transverse momenta. The decay vertex of the candidate B meson is also used along with the origin of the remaining tracks in the event. The difference between these vertices along the z-axis discriminates continuum events that have a common decay vertex and signal events whose decay vertices are displaced in the laboratory frame.

To obtain the signal yield an unbinned maximum likelihood fit to M_{bc} and ΔE is performed. The fit is performed simultaneously to three signal modes $(B \to (\rho,\omega)\gamma)$ plus the two $B \to K^*\gamma$ modes assuming isospin relations $B(B \to (\rho,\omega)\gamma) \equiv B(B^+ \to \rho^+\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}B(B^0 \to \rho^0\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}B(B \to \omega\gamma)$ and $(B^+ \to K^{*+}\gamma) = 2\frac{\tau_{B^+}}{\tau_{B^0}}B(B^0 \to K^{*0}\gamma)$, where $\frac{\tau_{B^+}}{\tau_{B^0}} = 1.083 \pm 0.017$ [5] is used. The five branching fractions, five background normalizations and five background ΔE slopes are floated in the fit.

Preliminary results of the simulataneous fit are shown in Table 1. The simultaneous fit gives a significance of 3.5σ, where significance is defined as $\sqrt{-2\ln(L_0/L_{\rm max})}$, $L_{\rm max}$ is the maximum likelihood in the M_{bc} fit, and L_0 is the likelihood of the best fit when the signal yield is constrained to be zero.

4 CP violation in radiative B decays

The measurement of CP violation can shed new light on the structure of this flavor-changing neutral-current both testing the SM predictive powers and constraining the parameter space of SM extensions. Time-dependent CP asymmetries in radiative penguin decays have been covered elsewhere [12] and are not discussed here due to lack of space.

Table 1: *Results of the efficiency, signal yield, significance and branching fraction from simultaneous and individual fits. All numbers are preliminary.*

Mode	efficiency (±syst.)	signal yield (±stat.±syst.)	significance	branching fraction (±stat.±syst.)×10^6
$B^+ \to \rho^+\gamma$	$(5.6 \pm 0.4)\%$	$15.5^{+7.1}_{-6.3} \pm 1.5$	2.5	$(1.8^{+0.8}_{-0.7} \pm 0.1)$
$B^0 \to \rho^0\gamma$	$(5.0 \pm 0.3)\%$	$3.6^{+3.6}_{-2.8}{}^{+0.7}_{-0.9}$	1.2	$(0.5^{+0.5}_{-0.4} \pm 0.2)$
$B \to \omega\gamma$	$(4.7 \pm 0.5)\%$	$8.9^{+4.8}_{-4.0} \pm 1.2$	2.3	$(1.3^{+0.7}_{-0.6} \pm 0.2)$
$B \to (\rho,\omega)\gamma$	–	–	3.5	$(1.8^{+0.6}_{-0.5} \pm 0.1)$

4.1 Direct CP violation in $\bar{B} \to X_s\gamma$ decays

In the SM the CP violation in the inclusive process $\bar{B} \to X_s\gamma$ can be reliably predicted [9]:

$$A_{\rm CP} = \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)} = 0.0044^{+0.0024}_{-0.0014} \qquad (3)$$

whereas in some supersymmetric scenarios sizable asymmetries ($A_{\rm CP} \sim 10\%$) are possible and natural. [13]

BaBar has studied this [14] using a sample of $(88.9 \pm 1.0) \times 10^6$ $B\bar{B}$ pairs. The $\bar{B} \to X_s\gamma$ sample is obtained by combining twelve fully reconstructed self-tagging decay channels:
$B^- \to K^-\pi^0\gamma,\ K^-\pi^+\pi^-\gamma,\ K^-\pi^0\pi^0\gamma, K^-\pi^+\pi^-\pi^0\gamma$ and
$\bar{B}^0 \to K^-\pi^+\gamma,\ K^-\pi^+\pi^0\gamma,\ K^-\pi^+\pi^0\pi^0\gamma,\ K^-\pi^+\pi^+\pi^-\gamma$ and
$B^- \to K^0_s\pi^-\gamma,\ K^0_s\pi^-\pi^0\gamma,\ K^0_s\pi^-\pi^0\pi^0\gamma,\ K^0_s\pi^-\pi^+\pi^-\gamma.$
Their charge conjugates are used to obtain the $B \to X_{\bar{s}}\gamma$ sample. Fully reconstructed $B \to X_{\bar{s}}\gamma$ decays are characterized by two kinematic variable m_{ES} (which is analagous to M_{bc} defined in an earlier section) and ΔE. The positive identification of charged kaons removes any contribution of $b \to d\gamma$. $A_{\rm CP}$ is obtained from the yield asymmetry between the B and $\bar{B}$ sample correcting for flavor misidentification and detector asymmetry.

A CP asymmetry of $(0.025 \pm 0.050 \pm 0.015)$ is measured, where the first error is statistical and the second is systematic, corresponding to an allowed range of $-0.06 < A_{\rm CP}(b \to s\gamma) < +0.11$ at the 90% confidence level and is in good agreement with SM predictions.

4.2 Search for CP or isospin asymmetries in the $B \to K^*\gamma$ decays

The set of exclusive decays $B \to K^*\gamma$ provide other oppurtunities to test the SM predictions for the isospin (Δ_{0-}, Eq. 4) and the CP asymmetries ($A_{\rm CP}$, Eq. 5):

$$\Delta_{0-} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)} \quad (4)$$

$$A_{\rm CP} = \frac{\Gamma(\bar{B} \to \bar{K}^*\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\bar{B} \to \bar{K}^*\gamma) + \Gamma(B \to K^*\gamma)} \quad (5)$$

The SM predicts a positive Δ_{0-} between 5 and 10% and $A_{\rm CP}$ less than 1% [13]. New physics contribution can modify these values significantly.

The K^* is reconstructed in self-tagging decay channels $K^{*0} \to K^+\pi^-$; $K^{*+} \to K^+\pi^0$, $K^0_s\pi^+$ and their charge conjugates. For the isospin analysis $K^{*0} \to K^0_s\pi^0$ was also used.

The signal yield and $A_{\rm CP}$ for each decay mode are determined from a two-dimensional extended unbinned maximum likelihood fit to the m_{ES} and ΔE^*. Δ_{0-} is determined from the signal yields correcting for the differences in signal efficiency and lifetime between the neutral and charged B. The preliminary results are:

$$A_{\rm CP} = -0.015 \pm 0.036(\text{stat.}) \pm (\text{syst.}) \quad (6)$$

$$\Delta_{0-} = +0.051 \pm 0.044(\text{stat.}) \pm 0.023(\text{syst.}) \pm 0.024(\text{R}^{+/0}) \quad (7)$$

the first error being statistical and the second the systematic error. The third error on Δ_{0-} is related to the uncertainty on the ratios recently measured by the BaBar collaboration [15] and accounts for the possibility of different production rates of charged and neutral B's.

5 Leptonic B decays

The study of purely leptonic B decays, $B^+ \to \ell^+\nu_\ell$, can provide sensitivity to poorly constrained SM parameters and also act as a probe for new physics. In the SM the reaction proceeds via the annihilation of the b and $\bar{u}$ producing an intermediate W boson which subsequently decays to a lepton and neutrino, the branching ratio is given by:

$$B(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B|V_{ub}|^2\tau_B, \quad (8)$$

where G_F is the Fermi constant, m_ℓ and m_B are the lepton and meson masses, f_B is the B decay constant, V_{ub} is the relevant CKM matrix element and τ_B is the B^+ lifetime. Currently f_B comes from lattice QCD calculations and is affected by a 15% uncertainty. Therefore, observation of $B^+ \to \ell^+\nu$ could provide the first direct measurement of f_B. Unfortunately, leptonic decays are strongly suppressed by helicity and there is, as yet, no experimental evidence for such decays.

5.1 $B^+ \to \tau^+\nu$

Using 88.9 million $B\bar{B}$ events BaBar has studied $B^+ \to \tau^+\nu$ using two statistically independent analysis techniques. Due to the presence of at least two neutrinos in the final state, the semileptonic ($B^- \to D^0\ell^-\bar{\nu}X$) and hadronic ($B^- \to D^0X_{\rm had}$) decays of the other B have been reconstructed, as for the $B^+ \to K^+\nu\bar{\nu}$ analysis.

After reconstructing the other B in the event the signal signature os given by one or up to three charged tracks, depending on the τ decay mode. Low remaining neutral energy, $E_{\rm extra}$, is demanded to limit backgrounds from processes depositing considerable energy in the calorimeter. For the semileptonic tag analysis [16], only the single prong leptonic τ decays are considered and a fit to $E_{\rm extra}$ is performed to extract the signal and background yields from data. In the analysis using the hadronic tag technique [17] τ decays into $\pi^+\bar{\nu}_\tau$, $\pi^+\pi^0\bar{\nu}_\tau$ and $\pi^+\pi^-\pi^+\bar{\nu}_\tau$ are also considered and the number of events with $E_{\rm extra} <$ 100 MeV is counted. Combining the two samples yields a preliminary upper limit on the branching fraction at the 90% confidence level of

$$B(B^+ \to \tau^+\nu) < 4.1 \times 10^{-4}, \qquad (9)$$

which represents the best upper limit on this channel.

5.2 $B^+ \to \mu^+\nu$

The $B^+ \to \mu^+\nu$ decay has been studied by BaBar using the same dataset as the $B^+ \to \tau^+\nu$ analyses. After identifying a muon, all remaining particles are associated with the decay of the other B. Once the other B is reconstructed, the muon momentum is calculated in the rest frame of the signal B. The signal muon momentum distribution peaks at 2.64 GeV/c. No significant signal excess has been observed and an upper limit on the branching fraction at the 90% confidence level of

$$B(B^+ \to \mu^+\nu) < 6.6 \times 10^{-6}, \qquad (10)$$

was set.

The Belle collaboration has also studied this channel using a similar method using 60 fb^{-1} of data and place a compatible limit of $B(B^+ \to \mu^+\nu) < 6.8 \times 10^{-6}$ at the 90% confidence level.

6 Conclusions

The unprecedented luminosities of the B-factories allows new extensive and detailed studies on processes involving flavor-changing neutral-current such as $b \to s\ell^+\ell^-$, $b \to s\gamma$ and $b \to d\gamma$. There is no experimental evidence for CP violation in $b \to s\gamma$ at the 5% level and the SM predicitions are confirmed. Both BaBar and Belle are collecting richer data samples that will permit more stringent tests of the SM through studies of radiative and leptonic B decays and there may be surprises in the very near future.

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