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Rare B Decays at *BABAR* and Belle

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We report on searches of rare B meson decays at the *BABAR* and Belle experiments using their full datasets. A recent search for the flavor-changing neutral-current decays $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ ($\ell = e$ or μ) from *BABAR* is discussed. Both *BABAR* and Belle have updated results on their searches for the flavor-changing neutral-current decays $B \to K^{(*)}\nu\overline{\nu}$. Belle also performed $B \to h^{(*)}\nu\overline{\nu}$ searches of other final-state hadrons $h^{(*)}$, and *BABAR* searched for the invisible decays $J/\psi \to \nu\overline{\nu}$ and $\psi(2S) \to \nu\overline{\nu}$. Results from a heavy neutrino search at Belle are also presented.

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1. Introduction

The *BABAR* [1] and Belle [2] experiments are performed at asymmetric e^+e^- B-factories using data from collisions at the $\Upsilon(4S)$ resonance in order to study flavour physics, including the properties and decays of B mesons. Together, the two experiments have collected over 1.1 ab^{-1} of data, corresponding to over 1.2 billion $B\bar{B}$ pairs. Such large data samples are expected to include B decays from rare processes, including several thousand events with branching fractions on the order of 10^{-6}.

One category of rare processes are flavor-changing neutral-current (FCNC) transitions, such as $b \to s\nu\bar{\nu}$, $b \to d\nu\bar{\nu}$, and $b \to d\ell^+\ell^-$, where $\ell = e$ or μ. These decays are theoretically well-understood and can provide precision tests of the Standard Model (SM). Since FCNC decays are prohibited at tree-level in the SM, they can only occur via penguin diagrams or one-loop box diagrams, as depicted in Figure 1. These processes are dominated by a top-quark exchange, which results in SM expected branching fractions that are suppressed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $|V_{ts}|$ or $|V_{td}|$. Therefore, $b \to s\nu\bar{\nu}$ transitions are expected in the SM to have a rate of $\mathcal{O}(10^{-6})$, while $b \to d\ell^+\ell^-$ processes are expected at $\mathcal{O}(10^{-8})$. The same final state can also occur in the SM via an intermediate quarkonium resonance, such as $b \to sc\bar{c}$, $c\bar{c} \to \nu\bar{\nu}$ which is also expected to have a SM branching fraction of $\mathcal{O}(10^{-8})$ [3]. All of these FCNC processes can be enhanced by new physics processes which could contribute at the same order as the SM processes, enabling sensitive searches for effects beyond the SM. Some examples include non-standard Z or Z' couplings, supersymmetric or other new physics particles entering into the penguin loops, and invisible dark matter candidates in lieu of final-state neutrinos [4, 5, 6, 7, 8].

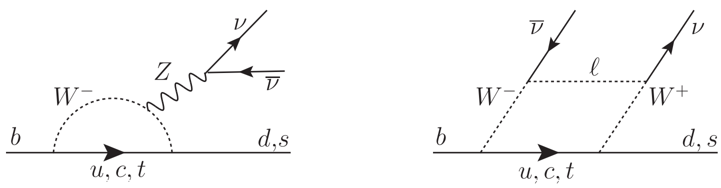

Figure 1: Lowest-order SM Feynman diagrams for $b \to d\nu\bar{\nu}$ and $b \to s\nu\bar{\nu}$ transitions. The diagrams for the FCNC decays $b \to d\ell^+\ell^-$ are similar, but include an additional electromagnetic penguin contribution from an off-shell photon coupling to $\ell^+\ell^-$.

Another category of rare processes are those due to new physics particles with small coupling strengths to the SM particles. One highly motivated particle, a heavy right-handed neutrino, could not only be a dark matter candidate but could also resolve several unanswered questions within particle physics. For example, in the Neutrino Minimal Standard Model (νMSM) [9], the addition of three right-handed neutrinos would enable a straight-forward inclusion of neutrino oscillations into the SM, three heavy neutrinos could explain the smallness of the observed neutrino masses due to the see-saw mechanism, and three heavy Majorana neutrinos could provide the necessary CP-violation to explain baryogenesis. The three right-handed neutrinos could mix with the three observed left-handed neutrino flavours via a matrix of elements $|U_{ij}|$ $(i, j = e, \mu,$ or $\tau)$ in an analogous way to the CKM matrix of the quark sector.

2. Flavor-Changing Neutral Current Decay Searches

2.1 $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ at BABAR

The expected SM branching fractions of the FCNC decays $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ (neglecting those occurring via an intermediate $c\bar{c}$ resonance) are on the order of 10^{-8} due to the CKM suppression of $|V_{td}|$. Therefore, only approximately 10 signal events are expected in the full BABAR dataset of 471 million $B\bar{B}$ pairs, unless a new physics scenario enhances the rates. A recent BABAR search [10] uses the full dataset to search for the decays $B^+ \to \pi^+\ell^+\ell^-$, $B^0 \to \pi^0\ell^+\ell^-$, and $B^0 \to \eta\ell^+\ell^-$, where ℓ is either an electron or a muon. An event is selected if it contains a lepton pair and a π or η candidate. Due to the large number of lepton pairs that are produced via the J/ψ and $\psi(2S)$ resonances, a veto is applied on the lepton pair invariant mass around these $c\bar{c}$ resonances. The vetoed events provide a high-statistics control sample for systematic uncertainty studies and branching fraction validations. Continuum background is suppressed using a neural net for each lepton channel, and two other neural nets are used to suppress $B\bar{B}$ backgrounds. Additional requirements are also applied to reduce specific background processes, such as the QED background $e^+e^- \to e^+e^-q\bar{q}$.

A two-dimensional unbinned maximum likelihood fit is applied to the $m_{\rm ES}$ and ΔE variables which describe the reconstructed signal B meson. The energy-substituted mass, $m_{\rm ES} \equiv \sqrt{E^2_{\rm beam} - \vec{p}^{\,2}_B}$, where $E_{\rm beam}$ is the center-of-mass (CM) energy and $\vec{p}_B$ is the three-momentum of the reconstructed signal B meson in the CM frame, peaks at the nominal B meson mass for well-reconstructed signal events. The variable $\Delta E \equiv E_B - E_{\rm beam}$, where E_B is the energy of the reconstructed B meson in the CM frame, peaks at zero for well-reconstructed signal events. $B \to K\ell^+\ell^-$ events, in which the kaon is mis-identified as a pion, peak at the nominal B meson mass in $m_{\rm ES}$, but are shifted to negative values of ΔE. Although the particle mis-identification rate is small, the branching fraction of $B \to K\ell^+\ell^-$ events is approximately 25 times larger than that of the signal, resulting in an expected $B \to K\ell^+\ell^-$ background contribution on the same order as the expected signal yield. Therefore, the $B \to K\ell^+\ell^-$ distributions are simultaneously fit with the $B \to \pi\ell^+\ell^-$ distributions, and the resulting $B \to K\ell^+\ell^-$ branching fractions provide validation to those obtained for the signal channels. In addition to fitting each of the six channels separately, lepton-flavor and isospin-constrained fits are also performed in order to combine the lepton channels and pion channels respectively.

The preliminary lepton-flavor constrained results of this search are presented in Table 1. This search sets the first upper limits at the 90% confidence level (CL) for the $B^0 \to \eta\ell^+\ell^-$ branching fractions. It also reports the most stringent upper limits to date for $\mathcal{B}(B^0 \to \pi^0\ell^+\ell^-)$. The upper limits obtained for $\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-)$ are only a factor of two to three times larger than the SM predictions of $\mathcal{B}(B^+ \to \pi^+\ell^+\ell^-)_{\rm SM} = (1.4-3.3)\times 10^{-8}$ and are consistent with the recent measurement of $\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-) = (2.4\pm 0.6\pm 0.2)\times 10^{-8}$ from the LHCb experiment [11].

2.2 $B \to h^{(*)}\nu\bar{\nu}$ at Belle

The search for $B \to h^{(*)}\nu\bar{\nu}$ decays (where $h^{(*)}$ is a charmless hadron) is experimentally challenging due to the presence of two neutrinos in the final state. However, due to the mostly hermetic detector at Belle and BABAR, one can detect the presence of neutrinos by identifying missing momentum within the event. In addition, one can exploit the clean $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ production at

Table 1: The lepton-flavor averaged preliminary *BABAR* branching fraction upper limits for $B \to \pi\ell^+\ell^-$ and $B \to \eta\ell^+\ell^-$ at the 90% CL. The isospin-constrained upper limit of $\mathcal{B}(B \to \pi\ell^+\ell^-)$ is also provided.

$B^+ \to \pi^+\ell^+\ell^-$	$B^0 \to \pi^0\ell^+\ell^-$	$B^0 \to \eta\ell^+\ell^-$
$< 6.6 \times 10^{-8}$	$< 5.3 \times 10^{-8}$	$< 6.4 \times 10^{-8}$
$< 5.9 \times 10^{-8}$		

the B-factories to reconstruct both B mesons within the event. *BABAR* and Belle both use a similar technique in which one B meson (B_{tag}) is fully reconstructed in hadronic modes, for example by adding kaons and/or pions to a $D^{(*)}$ meson "seed." The B_{tag} is required to be consistent with the m_{ES} and ΔE of a well-reconstructed B meson. Evidence of the signal B decay is then searched for within the remaining particles and missing energy within the event. This technique provides high purity samples of B mesons and fully determines the signal B rest frame for improved kinematic resolution. Although the technique suffers from a lower efficiency than other search methods, both Belle and *BABAR* have increased the B_{tag} reconstruction efficiency over past algorithms by a factor of two to three [12, 13].

A recent Belle search [14] for $B \to h^{(*)}\nu\bar{\nu}$, where $h^{(*)} = K^+, K_S^0, K^*, \pi^+, \pi^0, \eta, \rho^+, \rho^0$, or ϕ, was performed using the full dataset of 772 million $B\bar{B}$ pairs. The B_{tag} is first reconstructed hadronically before reconstructing or identifying the hadron candidate of the signal decay, and events with additional charged tracks or π^0 candidates are rejected. The hadron momentum, which is expected to be hard, is restricted between 1.6 and 2.5 GeV$/c$ in the signal B rest frame to reduce background. This restriction is applied to all decay channels except $B \to \phi\nu\bar{\nu}$ which lacks the theoretical form factor calculations necessary to determine the efficiency of such a restriction. After reconstructing both the B_{tag} and the hadron, there should be no additional detected energy in the event. The sum of all detected energy in the calorimeter that is unused in the event reconstruction (E_{ECL} or E_{extra}) peaks at zero for signal events and at higher energies for background events. A binned maximum likelihood is fit to the E_{extra} distribution to extract the signal yields.

The preliminary upper limits from this search are presented in Table 2. The branching fraction upper limits obtained for $B \to K^*\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$, and $B^0 \to \rho^0\nu\bar{\nu}$ are the most stringent limits to date. A negative signal yield is obtained in the $B \to K^*\nu\bar{\nu}$ channels, which approximately halves the previous upper limits from Belle and *BABAR*. These upper limits are only a factor of five higher than the SM predictions of $\mathcal{B}(B \to K^*\nu\bar{\nu})_{\text{SM}} = (0.68-1.3)\times 10^{-5}$. The $\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$ upper limit is approximately one third of the previous limit, and the limit on $\mathcal{B}(B \to \rho^0\nu\bar{\nu})$ is approximately half of the previous limit.

Table 2: Preliminary Belle branching fraction upper limits for $B \to h^{(*)}\nu\bar{\nu}$ at the 90% CL. The reported $B \to K_S^0\nu\bar{\nu}$ upper limit is doubled here to account for $\mathcal{B}(K^0 \to K_S^0)$ in order to compare with the *BABAR* $\mathcal{B}(B \to K^0\nu\bar{\nu})$ upper limit in Table 3.

$h =$	K	K^*	π	ρ	ϕ
$B^+ \to h^+\nu\bar{\nu}$	$< 5.5 \times 10^{-5}$	$< 4.0 \times 10^{-5}$	$< 9.8 \times 10^{-5}$	$< 21.3 \times 10^{-5}$	
$B^0 \to h^0\nu\bar{\nu}$	$< 19.4 \times 10^{-5}$	$< 5.5 \times 10^{-5}$	$< 6.9 \times 10^{-5}$	$< 20.8 \times 10^{-5}$	$< 12.7 \times 10^{-5}$

2.3 $B \to K^{(*)}\nu\bar{\nu}$ and Invisible Quarkonium Decays at BABAR

A recent BABAR search [15] for $B \to K^{(*)}\nu\bar{\nu}$, performed using the full dataset of 471 million $B\bar{B}$ pairs, also uses an hadronic reconstruction of the $B_{\rm tag}$. After reconstructing the $B_{\rm tag}$, and either identifying a K^+ or reconstructing a K_s^0 or K^* candidate, no additional tracks are permitted in the event. Continuum background is suppressed using a likelihood ratio of event-shape variables, and $B\bar{B}$ background is suppressed by restricting the $E_{\rm extra}$ values to less than a few hundred MeV. Due to the possibility that new physics scenarios could alter the kinematic spectrum, such as invisible scalars which could increase the observed number of low-momentum kaons [4], this search reports two results. For maximum SM sensitivity, one result requires that the kinematic variable s_B, defined as q^2/m_B^2 where q^2 is the invariant mass squared of the neutrino pair, be less than 0.3, which corresponds to a $K^{(*)}$momentum greater than about 1.7 (1.8) GeV/c. The second result reports partial branching fractions over the full kinematic spectrum in order to remain sensitive to new physics enhancements that may occur at higher q^2 values.

The results within the SM-sensitive low s_B region are presented in Table 3. This search obtains the most stringent upper limits on $\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$ using the hadronic tag reconstruction technique. A slight excess is observed in the $B^+ \to K^+\nu\bar{\nu}$ channel, corresponding to a significance of less than 2σ but providing the first lower limits at the 90% CL of $\mathcal{B}(B \to K\nu\bar{\nu})$. The partial branching fractions over the full kinematic spectrum set branching fraction upper limits on several new physics models at $\mathcal{O}(10^{-5})$. In addition, the Wilson coefficients $C^{\nu}_{L,R}$ describing the $q\bar{q} \to \nu\bar{\nu}$ four-point interaction, which can be affected by beyond-SM right-handed currents, are accessible through $B \to K^{(*)}\nu\bar{\nu}$. The lower limit on $B \to K\nu\bar{\nu}$ significantly reduces the parameter space for these Wilson coefficients, although the SM expected values are still consistent with the allowed parameter space.

Table 3: Preliminary BABAR branching fraction limits for $B \to K^{(*)}\nu\bar{\nu}$ at the 90% CL within the region $s_B < 0.3$. Combined limits, assuming equal branching fractions for the charged and neutral channels, are also presented.

$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$	$B^+ \to K^{*+}\nu\bar{\nu}$	$B^0 \to K^{*0}\nu\bar{\nu}$
$(>0.4, <3.7)\times 10^{-5}$	$<8.1\times 10^{-5}$	$<11.6\times 10^{-5}$	$<9.3\times 10^{-5}$
$(>0.2, <3.2)\times 10^{-5}$		$<7.9\times 10^{-5}$	

The rare decay $B \to K^{(*)}\nu\bar{\nu}$ can also be produced via the narrow $c\bar{c}$ resonances. Therefore, searches for $c\bar{c} \to \nu\bar{\nu}$, where $c\bar{c} = J/\psi$ or $\psi(2S)$, via $B \to K^{(*)}J/\psi$ or $B \to K^{(*)}\psi(2S)$ decays are performed using the same event selection as for the $B \to K^{(*)}\nu\bar{\nu}$ search but with the requirement that the invarient mass of the neutrino pair is consistent with a $c\bar{c}$ resonance mass. This search sets the first upper limit on $\mathcal{B}(\psi(2S) \to \nu\bar{\nu})$ at $< 15.5\times 10^{-3}$.

3. New Physics Decay Searches

3.1 Heavy Neutrinos at Belle

If heavy neutrinos ν_h exist, it is a well-motivated assumption that they might mix with the three observed neutrino flavors, ν_ℓ. A recent Belle search [16] using the full dataset searches for

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evidence of the production of an on-shell heavy neutrino which decays via $\nu_h \to \nu_{\ell_1} \to \pi^+\ell_1^-$. Since heavy neutrinos are expected to have long flight lengths, potentially decaying beyond the detector, an inclusive $B \to X\ell_2\nu_{\ell_2}$ ($\nu_{\ell_2} \to \nu_h$) reconstruction is employed to increase the detection efficiency, where X can be a $D^{(*)}$ meson, an up-quark meson such as π, ρ, or η, or nothing such that the B meson decays leptonically. If the heavy neutrino is a Dirac fermion, the two charged leptons in the event would necessarily be oppositely charged, and if it is a Majorana fermion, the lepton charges could be either the same or opposite.

Events are selected by searching for an oppositely charged lepton and pion, and a second lepton of any charge. To reduce background, the lepton and pion pair is required to form a vertex displaced from the interaction region due to the long expected flight length of the heavy neutrino, while the second lepton must originate from the interaction region. Below a ν_h mass of $2\,\mathrm{GeV}/c^2$, the $B \to D^{(*)}\ell\nu$ process is expected to dominate the ν_h production. The leptonic and light semi-leptonic decays suffer from high backgrounds within this same region. Therefore, only $B \to D^{(*)}\ell\nu$ decays are reconstructed for ν_h masses below $2\,\mathrm{GeV}/c$, and a mass constraint is applied to the reconstructed $D^{(*)}$ meson to further reduce the combinatorial background in this region.

The 11 observed data events are consistent with the expected background and are evaluated in mass bins of $3\,\mathrm{MeV}/c^2$. The preliminary upper limits are most stringent at a ν_h mass of $2\,\mathrm{GeV}/c^2$, where $\mathcal{B}(B \to X\ell\nu_h)\cdot\mathcal{B}(\nu_h \to \pi\ell) < 7.5\times10^{-7}$ at 90% CL. The upper limits on the coupling strengths between ν_h and ν_ℓ are compatible with previous measurements by a variety of other experiments.

4. Conclusion

Although FCNC decays such as $B \to K^{(*)}\nu\bar{\nu}$, $B \to \pi\nu\bar{\nu}$, and $B \to \pi\ell^+\ell^-$ are suppressed in the SM, they are theoretically well-understood and sensitive to enhancements from physics beyond the SM. Both *BABAR* and Belle have used their full datasets to set stringent upper limits on these experimentally-challenging decays. The upper limits for many of these rare FCNC decays are now at the same order of magnitude as the SM expected branching fraction values, yet no signal decay in these rare modes has been observed at the B-factories. A larger dataset is required to measure these decays, such as the approximately $50\,\mathrm{ab}^{-1}$ of data expected to be collected by the Belle II experiment [17]. Once the statistical limitations are overcome, rare B meson decays will offer a rich avenue of new precision probes into beyond-SM effects, such as from additional FCNC loop contributions, or via the production of invisible scalars or heavy neutrinos.

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