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Probing QCD with rare charmless B decays

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Abstract

Rare charmless hadronic B decays are a good testing ground for QCD. In this paper we describe a selection of new measurements made by the *BABAR* and BELLE collaborations.

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1 Introduction

Rare charmless hadronic B decays are a good testing ground for the standard model. The dominant amplitudes contributing to this class of B decays are CKM suppressed tree diagrams and $b \to s$ or $b \to d$ loop diagrams ('penguins'). These decays can be used to study interfering standard model (SM) amplitudes and CP violation. They are sensitive to the presence of new particles in the loops, and they provide valuable information to constrain theoretical models of B decays.

The B factories *BABAR* at SLAC and Belle at KEK produce B mesons in the reaction $e^+e^- \to \Upsilon(4S) \to B\overline{B}$. So far they have collected integrated luminosities of about $600\,\mathrm{fb}^{-1}$ and $380\,\mathrm{fb}^{-1}$, respectively. The results presented here are based on subsets of about 200–350 fb^{-1} and are preliminary unless a journal reference is given.

2 ΔS from rare decays

The time-dependent CP asymmetry in B decays is observed as an asymmetry between B^0 and $\overline{B}^0$ decay rates into CP eigenstates f

$$\mathcal{A}_{cp}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to f) + \Gamma(B^0 \to f)} = S_f \sin \Delta m_d \Delta t - C_f \cos \Delta m_d \Delta t, \quad (1)$$

where $\Delta m_d = 0.502 \pm 0.007\mathrm{ps}^{-1}$ and Δt is the time difference between the decays of the two neutral B mesons in the event. The coefficients S_f and C_f depend on the final state f; for the 'golden' decay $B^0 \to J/\psi K^0_S$, for example, $S_{J/\psi K^0_S} = \sin 2\beta$, $C_{J/\psi K^0_S} = 0$. Here, $\beta \equiv \phi_1$ is one of the angles of the unitarity triangle of the CKM matrix. In general, the presence of more than one contributing amplitude for the decay can introduce additional phases, such that S_f measured in such a decay deviates from the simple $\sin 2\beta$. There are intriguing hints in experimental data that S_f is smaller than $\sin 2\beta$ in B decays involving the transition $b \to q\overline{q}s$, like $B^0 \to \phi K^0$, $B^0 \to \eta' K^0$, or $B^0 \to \pi^0 K^0$. However, for each of these final states the SM contribution to $\Delta S_f \equiv S_f - \sin 2\beta$ from sub-dominant amplitudes needs to be determined in order to draw a conclusion about the presence of any new physics. Typically, models prefer $\Delta S_f > 0$ [1, 2], while for the final state $\eta' K^0_S$, a small, negative ΔS_f is expected[3]. Measuring B decays which are related to the ones above by approximate SU(3) flavor or isospin symmetries helps to constrain the expected ΔS_f.

The sub-dominant contributions to $B^0 \to \phi K^0$ can be constrained using SU(3) flavor relations[4]. This requires branching fraction measurements for eleven decay channels ($K^{*0}\overline{K}^0, \overline{K}^{*0}K^0$, and hh' with $h = \rho^0, \omega, \phi$ and $h' = \pi^0, \eta, \eta'$). *BABAR* has measured an upper limit[5] for the sum $\mathcal{B}(K^{*0}\overline{K}^0) + \mathcal{B}(\overline{K}^{*0}K^0) < 1.9 \times 10^{-6}$ and an updated upper limit[6] for $\phi\pi^0$ of $\mathcal{B}(\phi\pi^0) < 2.8 \times 10^{-7}$. This allows one to place a bound on $|\Delta S_{\phi K^0}| < 0.43$.

The decays $B^0 \to \eta^{(\prime)}\pi^0, \eta'\eta$ can be used to constrain the SM pollution in $B^0 \to \eta' K^0$, The expected branching fractions are between 0.2 and 1×10^{-6} for $\eta^{(\prime)}\pi^0$ and 0.3 - 2×10^{-6} for $\eta'\eta$. Using $211\,\mathrm{fb}^{-1}$ of data, *BABAR* sets the following upper limits[7] at 90% confidence level (C.L.) in units of 10^{-6}: $\mathcal{B}(B^0 \to \eta\pi^0) < 1.3$, $\mathcal{B}(B^0 \to \eta'\eta) < 1.7$, $\mathcal{B}(B^0 \to \eta'\pi^0) < 2.1$, while Belle[8] measures $\mathcal{B}(B^0 \to \eta'\pi^0) = (2.79^{+1.02+0.25}_{-0.96-0.34}) \times 10^{-6}$ with 386×10^6 analyzed $B\overline{B}$ pairs. Following Ref. [9], the expected improvement on the prediction of $\Delta S_{\eta' K^0_S}$ is about 20%, with a similar improvement for the measurement of $\sin 2\alpha$ in $B^0 \to \pi^+\pi^-$. Belle also measure $\mathcal{B}(B^0 \to \eta'\pi^0) = (2.79^{+1.02+0.25}_{-0.96-0.34}) \times 10^{-6}$.

Decays like $B^0 \to K^0_S K^0_S K^0_S$ only proceed via a $b \to s\overline{s}s$ penguin diagram. In these decays, SM pollution is therefore avoided altogether, making them a very clean probe for new physics. The related decay $B^0 \to K^0_S K^0_S K^0_L$ was studied by *BABAR*. It is already experimentally known that the resonant contribution from $\phi(\to K^0_S K^0_L)K^0_S$ to this decay is small, but the non-resonant component may be large[10]. Assuming a uniform Dalitz distribution and analysing $211\,\mathrm{fb}^{-1}$, *BABAR*[11] sets a 90% CL upper limit of $\mathcal{B}(B^0 \to K^0_S K^0_S K^0_L) < 6.4 \times 10^{-6}$. Due to a low product of efficiency and daughter branching fraction, this decay is of limited use for the understanding of CP violation in $b \to q\bar{q}s$ decays.

3 Measurements related to α

Decays containing a $b \to u$ transition can be used to measure the angle $\alpha \equiv \phi_2$ in the unitarity triangle. In general several amplitudes contribute to these decays, only allowing the direct measurement of an effective parameter α_{eff}. There are several methods to extract the true angle α in presence of this 'pollution.' For $B^0 \to \rho^+\rho^-$, isospin symmetry in B decays to $\rho\rho$ can be used to measure the shift $2\delta\alpha$. The previously available world averages for the branching fractions[12] were hard to reconcile with isospin symmetry. This has changed with new results from both B factories: the Belle collaboration[13] measures $\mathcal{B}(B^0 \to \rho^+\rho^-) = (22.8 \pm 3.8^{+2.3}_{-2.6}) \times 10^{-6}$. *BABAR* has a preliminary result of $\mathcal{B}(B^+ \to \rho^+\rho^0) = (17.2 \pm 2.5 \pm 2.8) \times 10^{-6}$. Both decays are found to be almost entirely longitudinally polarized. With the new branching fractions, the isospin triangles close.

Another new decay studied by *BABAR* and Belle is $B^0 \to a_1^\pm \pi^\mp$, from which α can be extracted up to a four-fold ambiguity. Exploiting isospin or approximate SU(3) flavor symmetries this ambiguity can be overcome[14]. This needs also the measurement of related axial–vector decays, from which a model-dependent measurement of α can be derived. *BABAR* searches for $B^0 \to a_1^\pm \pi^\mp$ in $211\,\mathrm{fb}^{-1}$ and measures[15] a branching fraction of $\mathcal{B}(B^0 \to a_1^\pm \pi^\mp) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$, assuming $\mathcal{B}(a_1^+ \to (3\pi)^+) = 1$. This is confirmed by Belle[16]. The next step is to extend this analysis to measure time-dependent CP violation in this decay.

4 Other charmless B decays

The naive expectation for the longitudinal polarisation f_L in B decays into two vector mesons is $f_L \sim 1 - m_V^2/m_B^2$, which is fulfilled to a good approximation in tree-dominated decays such as $B \to \rho\rho$. There seems to be a pattern emerging where f_L is smaller than the naive expectation in decays dominated by loop diagrams. This was first seen in the decays $B \to \phi K^*$ where $f_L \approx 0.5$. To establish whether loop-induced decays generally have a lower f_L, *BABAR* has searched[17] for the related decays $B \to \omega V$, where $V = \rho, K^*, \omega, \phi$. Only $B^+ \to \omega\rho^+$ was observed with $\mathcal{B}(B^+ \to \omega\rho^+) = (10.6 \pm 2.1^{+1.6}_{-1.0}) \times 10^{-6}$. In this decay, $f_L = 0.82 \pm 0.11 \pm 0.02$ was found.

In B decays to final states comprising $\eta^{(\prime)}K^{(*)}$ the effect of the η–η' mixing angle combines with differing interference in the penguin diagrams to suppress the final states ηK and $\eta' K^*$, and enhance the final states $\eta' K$ and ηK^*. *BABAR* finds evidence for the decays $B \to \eta' K^*$ in $211\,\mathrm{fb}^{-1}$ and measures branching fractions of $\mathcal{B}(B^+ \to \eta' K^{*+}) = (4.9^{+1.9}_{-1.7} \pm 0.8) \times 10^{-6}$ and $\mathcal{B}(B^0 \to \eta' K^{*0}) = (3.8 \pm 1.1 \pm 0.5) \times 10^{-6}$. For the related decays into $\eta'\rho$, only $B^+ \to \eta'\rho^+$ is seen with $\mathcal{B}(B^+ \to \eta'\rho^+) = (6.8^{+3.2+3.9}_{-2.9-1.3}) \times 10^{-6}$, while $B^0 \to \eta'\rho^0$ is small with a 90% C.L. upper limit of $\mathcal{B}(B^0 \to \eta'\rho^0) < 3.7 \times 10^{-6}$. Theoretical predictions using SU(3) flavor symmetry[18], QCD factorization[19], and perturbative QCD factorisation[20] agree within errors with the observed branching fractions.

5 Summary

Charmless hadronic B decays provide a rich field for tests of QCD and the standard model of electroweak interactions. They allow to constrain the SM contribution to ΔS_f in loop-dominated B decays and precision tests of QCD models. With the currently analyzed statistics, decays with branching fractions of the order of 10^{-6} are within experimental reach.

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