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CP Violation, Mixing and Lifetime Results from *BaBar*

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The $BaBar$ collaboration has analysed 60M $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance at the PEP II asymetric collider at SLAC. Using this data sample we have measured the CP violation parameters $\sin(2\beta) = 0.75 \pm 0.09_{STAT} \pm 0.04_{SYST}$ and $|\lambda| = 0.92 \pm 0.06_{STAT} \pm 0.02_{SYST}$ from $B^0 \to c\overline{c} + K^{0(*)} + c.c.$ decays. From charmless 2-body B decays we measure $A_{K\pi} = -0.05 \pm 0.06 \pm 0.01(-0.14, +0.05)$,$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07(-0.66, +0.62)$, $C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07(-0.54, +0.48)$.
A number of B lifetime and mixing parameters, extracted from subsamples of this data set, are also presented.

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1 Introduction

B factories like PEP II produce vast quantities of B pairs, and allow the properties of the B meson to be studied in unprecedented detail. Of particular interest are the CP violating aspects of its behavior. CP violation in the b sector was first observed at BaBar in the summer of 2001 with the measurement of $\sin(2\beta)$ from $B^0 \to c\overline{c} + K^{0(*)} + c.c.$ [1]. With increasing datasets, $\sin(2\beta)$ can be measured with ever greater accuracy. Also, we can move on to our next goal in the study of CP violation in the b sector, the measurement of the parameter α.

In addition, many other aspects of B meson behavior can be studied, such as B lifetime and $B^0\overline{B^0}$ mixing. The methods needed to extract values for these quantities are similar to those used in CP analysis, and many techniques are common to both.

2 Time Evolution of the B

For charged Bs, evolution with time is a simple matter of exponential decay (decay amplitude $f(\Delta t) = \frac{1}{\tau_{B^\pm}} e^{-\Delta t/\tau_{B^\pm}}$). Neutral Bs can mix, changing flavor $B^0 \to \overline{B^0} + c.c.$, complicating their behavior ($f_\pm(\Delta t) = \frac{1}{4\tau_{B^0}} e^{-\Delta t/\tau_{B^0}} \times (1 \pm \cos(\Delta m_d \Delta t))$, where +/- stands for $B^0/\overline{B^0}$ and Δm_d is the mass difference between the heavy and light mass eigenstates). Where CP violation occurs (in decays to appropriate CP eigenstates) the decay amplitude is described by $f(\Delta t)_\pm = \frac{1}{4\tau_{B^0}} e^{-\Delta t/\tau_{B^0}} \times (1 \pm S\sin(\Delta m_d \Delta t) \pm C\cos(\Delta m_d \Delta t))$, where S and C are constants which depend upon the final CP eigenstates. C is a measure of the direct CP violation (CP violation in decay) occuring in the given decay, and S is determined by CP violation from the interference between mixing and decay.

3 The Dataset

The data used were collected with the BaBar detector. Different datasets were used with different analysis: the CP results use approximately $56fb^{-1}$ of data taken at the $\Upsilon(4S)$ resonance, the Mixing result using fully reconstructed hadronic events shown here uses $30fb^{-1}$ and other results use $20fb^{-1}$.

The BaBar detector is described in detail elsewhere [2].

4 Common Techniques

There are several general methods used in some or all of the analysis that will be discussed here.

4.1 Measurement of Δt

At BaBar, the measurement of Δt (the decay time difference between the first and second B to decay) relies heavily on the boost to the centre of mass brought about by PEP II's asymmetric design. Bs produced in pairs from the decay of the $\Upsilon(4S)$ resonance are almost at rest in the centre of mass. Thanks to the boost, they fly almost straight down the z axis of the detector. If the boost and the separation in z of the 2 Bs decay vertices are known, then Δt is known (to within small corrections).

Where a B is reconstructed, a least χ^2 fit is formed on all the tracks used in that reconstruction to find the vertex of that B. To find the vertex of the other B in the event, all remaining tracks (those not used in the reconstruction) also have a least χ^2 fit performed on them. Since decays of the $\Upsilon(4S)$ produce two Bs and nothing else, they must form the vertex of the other B. Tracks which contribute too large a value to the χ^2 are removed, as are those thought likely to come from K_s, Λ or conversions.

The average separation of the B vertices is $250\mu m$. Where a B is reconstructed, is vertex position can be measured with an error of $70\mu m$, where a B vertex is formed from leftover tracks the error is $180\mu m$. The error on Δt is therefore a significant fraction of Δt. As a result in fits the Δt dependent decay rate must be convoluted with a resolution function. At $BaBar$ we use resolution functions paramaterised in terms of event by event errors. The exact model used varies between analysis.

4.2 Flavor tagging

Mixing and CP measurements require knowledge of the flavor of the decaying Bs in addition to Δt. In some cases, where a B is reconstructed its flavor can be deduced from its mode of decay. To measure the flavor of an *un*reconstructed B, we infer it from its decay products using leftover tracks in the event. Several different methods are used. If a high energy lepton is observed amongst the decay products, the flavor of the B is very accurately determined by its charge ($l^- \Rightarrow B^0$ + c.c.). The presence of a charged Kaon is also a tell tale ($K^- \Rightarrow B^0$ + c.c.). If neither of these methods give an answer, we use a neural net technique (which gathers its information mostly from the charge of slow pions and unidetified leptons).

These methods are only of finite accuracy, and when flavor is measured incorrectly it leads to a diluting effect on the final measurement. Fortunately, this dilution can be measured in the process of performing a mixing fit, and this measured dilution can then be used as a correction factor in measurements of CP asymmetries.

4.3 Samples

The $B^0 \to c\overline{c} + K^{0(*)} + c.c.$ sample is of particular importance for measurement of $\sin(2\beta)$. In this sample, one of the Bs can be fully reconstructed and be seen to have decayed to Charmonium (J/ψ, $\psi(2S)$, χ_{c1}) and to either K_s (CP odd, $\eta = -1$) or K_L(CP even, $\eta = 1$). A plot of the energy substituted B mass from this sample is shown in Fig. 1. The Charmless two body B decay sample uses the CP eigenstates $B^0 \to \pi\pi, K\pi$ and KK.

The fully reconstructed hadronic sample uses decays that identify the flavor of the decaying B. We use $\overline{B^0} \to D^{(*)+}\pi^-, D^{(*)+}\rho^-, D^{(*)+}a1^-, J/\psi \overline{K^{*0}} + c.c$ and $B^- \to D^{(*)0}\pi^-, J/\psi K^-, \psi(2S)K^- + c.c.$, where $D^{*+} \to D^0\pi^+$, $D^{*0} \to D^0\pi^0$, $D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^0_S\pi^+\pi^-, K^-\pi^+\pi^-\pi^+$, $D^+ \to K^-\pi^+\pi^+, K^0_s\pi^+$, $\overline{K^{*0}} \to K^-\pi^+$ (all + c.c.). These provide enormous (10^4) event samples.

Greater efficiency can be provided by partial reconstruction techniques, albeit with correspondingly poorer purity. To form the partially reconstructed $B^0 \to D^{*-}\rho^+, D^{*-}\pi^+$ sample, no attempt is made to reconstruct the D^0 that the D^* decays to, instead its mass is deduced using the tightly constrained kinematics that result from working at the $\Upsilon(4S)$. Likewise the partially reconstructed semi-leptonic B sample chooses events with a fast lepton and a slow pion that are consistent with $B^0 \to D^* l\nu$ decay. The dilepton analysis takes this to its extreme by requir-

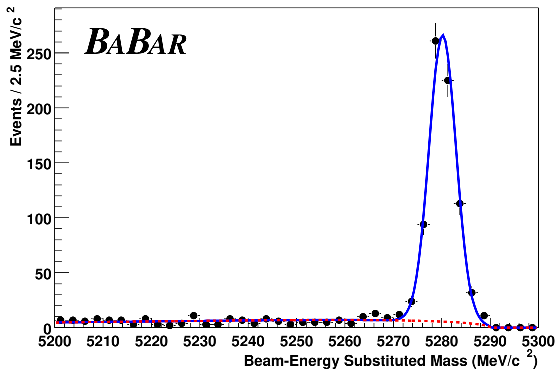

Figure 1: M_{es}distributions for $B^0 \to c\bar{c}K_s$. Fit is Gaussian for signal, Argus (phase space) for combinatoric background.

ing only two fast leptons (looking for cases where both Bs have decayed semi-leptonic+ly, 1% of B decays).

5 $B^0$and $B^{\pm}$ Lifetimes

A number of B lifetime measurements have been made at *BaBar*. Some are presented here. From hadronic, fully reconstructed B decays $\tau_{B^0} = 1.546 \pm 0.032 \pm 0.022 ps$, $\tau_{B^{\pm}} = 1.673 \pm 0.032 \pm 0.023 ps$,$\tau_{B^0}/\tau_{B^{\pm}} = 1.082 \pm 0.026 \pm 0.012$. Here the resolution function is the largest systematic uncertainty. From partially reconstructed $D^*\pi$ $\tau_{B^0} = 1.510 \pm 0.040 \pm 0.038 ps$ and from partially reconstructed $D^*\rho$ $\tau_{B^0} = 1.616 \pm 0.064 \pm 0.075 ps$. In this case the systematic error is dominated by the lack of Monte Carlo statistics and the constitution of the background. Partially reconstructed semi-leptonic B decays give a value of $\tau_{B^0} = 1.529 \pm 0.012 \pm 0.029 ps$ with the largest systematic errors being the impact of the choice of resolution model . The *BaBar* dilepton analysis gives $\tau_{B^0} = 1.557 \pm 0.028 \pm 0.027 ps$,$\tau_{B^{\pm}} = 1.655 \pm 0.026 \pm 0.027 ps$,$\tau_{B^0}/\tau_{B^{\pm}} = 1.064 \pm 0.031 \pm 0.026$, and in this analysis the resolution and background models dominate the systematic error.

6 $B^0\overline{B^0}$ Mixing

BaBar has made a number of measurements of B^0 mixing. From fully reconstructed hadronic B decays, $\Delta m_d = 0.516 \pm 0.016 \pm 0.010 ps^{-1}$ with the uncertainty in the value of the B^0 lifetime (taken from [3]) an the possible effects of tracking misalignment dominating the error. The dilepton analysis gives a value of $\Delta m_d = 0.493 \pm 0.012 \pm 0.009 ps^{-1}$. Again, the B^0 lifetime is a significant source of systematic error, as is the parameterization of the resolution function.

7 $\sin(2\beta)$ from $B^0 \to c\bar{c} + K^{0(*)}$

This analysis uses the sample of $B^0 \to$Charmonium K_s (or K_l or K^{*0}) + c.c. CP eigenstates described in section 4.3. For these CP eigenstates, the decay is predicted to be dominated by a single tree diagram, making direct CP violation an insignificant effect. In terms of the formalism described in section 2, this means that $C = 0$. Also, for these decays, $S = \sin(2\beta)$, making a measurement of time dependent CP violation in decays to these eigenstates a theoretically clean measurement of the CKM parameter β[4].

In addition to the sample of decays to CP eigenstates, we use the hadronic B sample to evaluate the dilution effect from wrongly measured flavor. To extract the value of $\sin(2\beta)$ whilst also fitting for the resolution function and the flavor tagging dilution (both of which may vary depending on the method used to tag the flavor) we use a 34 parameter fit. We fix Δm_d and τ_{B^0} to the values quoted in [3].

Using this method, we obtain a value for $\sin(2\beta)$ of $0.75 \pm 0.09_{STAT} \pm 0.04_{SYST}$. This is entirely in line with standard model expectations. Figure 2 shows graphicly the asymmetry results. The time dependent asymmetry can be clearly seen here.

The chief systematics are the uncertainty in Δm_d and τ_{B^0}, the properties of the background, and the effect of possible misalignment of our vertex tracker system.

To check the assumption that $C = 0$, we repeat the fit, allowing for the addition of a cosine term (allowing $C \neq 0$). We state this measurement in terms

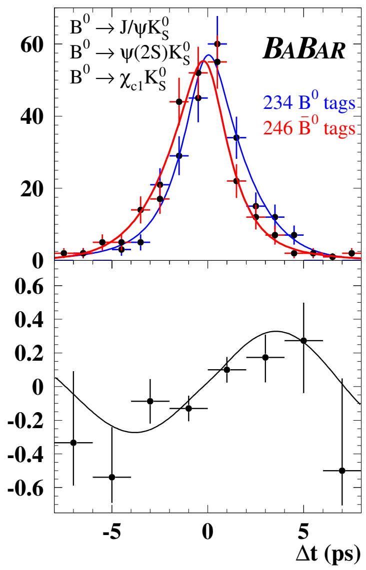

Figure 2: Δt for $B^0$and $\overline{B^0}$ (top), $\frac{\Delta t(B^0)-\Delta t(\overline{B^0})}{\Delta t(B^0)+\Delta t(\overline{B^0})}$ (bottom), $\eta = -1$ eigenstates.

of $|\lambda|$, where $C = (1-|\lambda|^2)/(1+|\lambda|^2)$. We measure $|\lambda| = 0.92 \pm 0.06_{STAT} \pm 0.02_{SYST}$, consistent with the absence of direct CP violation in these decays and therefore in line with the standard model.

8 $\sin(2\alpha)$ and Direct CP Violation From $B^0 \to h^+h^-$

It should be possible to extract $\sin(2\alpha)$ from the time dependant decay rate of $B^0 \to \pi^+\pi^-$decays in much the same way that $\sin(2\beta)$ is measured using $B^0 \to c\bar{c} + K^{0(*)}$ decays [4]. *BaBar* does indeed perform an analysis using $B^0 \to \pi^+\pi^-$ similar to that for used for $\sin(2\beta)$, but there are some significant differences. In these decays, we cannot assume that a single diagram dominates. We would expect both $S_{\pi\pi}$ and $C_{\pi\pi}$ (as defined in section 2) to be nonzero, also $\sin(2\alpha)$ is *not* simply $S_{\pi\pi}$, and cannot be trivially extracted. Instead, we quote results in terms of $S_{\pi\pi}$ and $C_{\pi\pi}$.

In addition there are technical differences. Background is much higher, and distinguishing $\pi\pi$ and

Mode	Yield (events)	BF (10^{-6})
$B^0 \to \pi\pi$	124^{+16+7}_{-15-9}	$5.4 \pm 0.7 \pm 0.4$
$B^0 \to K\pi$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$
$B^0 \to KK$	$< 15.6 (90\% C.L.)$	$< 1.1 (90\% C.L.)$

Table 1: Two Body Branching Fractions

$K\pi$ is important - misidentification would distort the result.

The analysis is done in two stages. First, the branching fractions for $\pi\pi$, $K\pi$ and KK are determined, and $A_{K\pi}$ (direct CP in the $K\pi$ mode) measured. This leads to the results shown in table 1 and the measurement of $A_{K\pi}$ as $-0.05 \pm 0.06_{STAT} \pm 0.01_{SYST}$. Next, a fit is performed for $S_{\pi\pi}$ and $C_{\pi\pi}$, with the results $S_{\pi\pi} = -0.01 \pm 0.37_{STAT} \pm 0.07_{SYST}(-0.66, +0.62)$, $C_{\pi\pi} = -0.02 \pm 0.29_{STAT} \pm 0.07_{SYST}(-0.54, +0.48)$. No significant CP violation is seen here. The dominant systematic of this analysis comes from K/π separation.

9 Conclusion

We have presented a series of measurement of B lifetime, mixing amplitude and the CP violation parameters $\sin(2\beta)$, $|\lambda|$, $S_{\pi\pi}$, $C_{\pi\pi}$ and $A_{K\pi}$. $\sin(2\beta)$ is measured with increased accuracy. No CP violation is yet seen in $B^0 \to \pi\pi$ or $K\pi$.

References

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