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Recent results on CP violation from BaBar

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The BABAR experiment at the PEP-II B factory at SLAC has collected over 37 10^6 $B\bar{B}$ pairs in the years 2000 and 2001. Based on this data sample, various studies of CP violation in the B system are presented, including the first observation of CP violation outside the kaon system and a measurement of the CKM parameter $\sin(2\beta) = 0.59 \pm 0.14(stat) \pm 0.05(syst)$. Studies on direct CP violation and CP violation in mixing are also presented.

1 Introduction

The violation of the CP symmetry was discovered many decades ago in the K^0 sector [1]. The importance of establishing the source and nature of this effect are manyfold. CP violation is an essential ingredient for the baryogenesis, explaining the present asymmetry in the universe between matter and anti-matter. In the framework of the Standard Model CP violation can be accomodated through a phase of the CKM matrix [2]. In this way CP violation is related to the origin of the masses and therefore to the electro-weak symmetry breaking mechanism. This sector of the Standard Model is of extreme interest as it may give us some clues of the physics beyond the standard model itself. Finally new physics can modify the CKM picture of CP violation and therefore precision tests are necessary.

The primary goal of the BABAR experiment at the PEP-II B factory at SLAC is to study CP violation in the B^0 meson system and to measure the sides and the angles of the unitarity triangle. This will allow to overconstrain the elements of this triangle and therefore to fully probe the Standard Model picture of CP violation.

Based on large data sample and on the excellent data quality, tests of the CPT symmetry can also be performed as briefly explained in section 7.

2 CP violation in B decays

CP violation can manifest itself in three different ways in the B system [2]:

- CP violation in decay, also called direct CP violation, when the amplitude for a decay and its CP conjugate have different magnitudes;

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- CP violation in mixing, which occurs when the two neutral mass eigestates are different from the CP eigenstates;

- CP violation in the interference between mixing and decays, which occurs in decays into final states that are common to B^0 and $\bar{B}^0$.

The last process is very important for BABAR: it leads to a time dependent asymmetry which vanish for time integrated variables. Results for the three kinds of asymmetry are presented here.

3 The PEP-II B Factory and the BABAR detector

The PEP-II B Factory is an e^+e^- colliding beam storage ring complex on the SLAC site designed to produce a nominal luminosity of 3 10^{33} $cm^{-2}s^{-1}$ at the mass of the $\Upsilon(4S)$ resonance i.e. 10.58 GeV, the $\Upsilon(4S)$ decaying in $B\bar{B}$ pairs. The machine is asymmetric with a 9.0 GeV electron beam and 3.1 GeV positron beam, corresponding to a $\beta\gamma$ factor of 0.56. The total luminosity recorded in the years and 2000 and 2001 (as of july 2001) corresponds to 37.7 fb^{-1} (more than 37 10^6 $B\bar{B}$ pairs).

The BABAR detector is described in more details elsewhere [3]. Inside the superconducting solenoid producing a 1.5 T axial magnetic field are:

- a five layer silicon strip vertex detector (SVT), with a typical resolution of 10 μm per hit;

- a central drift chamber (DCH), giving a momentum resolution $\sigma(p_T)/p_T = 0.0013p_T + 0.0045$;

- a quartz-bar Cherenkov radiation detector (DIRC) for charged hadron identification giving a $K - \pi$ separation larger than 3.4 σ for momenta below 3.5 GeV/c;

- a CsI crystal electromagnetic calorimeter;

- an Instrumented Flux Return (IFR) which allows to identify muons and to reconstruct K_L^0 hadronic showers.

4 Observation of CP violation in the B system

4.1 The golden mode

CP violation in the interference between mixing and decays is controlled by a single complex parameter $\lambda = \eta_f \frac{q}{p} \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$ where η_f is the CP eigenvalue of the

final state f_{CP},$\frac{q}{p}$ is a factor which depends on the $B-\bar{B}$ mixing and $A_{f_{CP}}$ and $\bar{A}_{\bar{f}_{CP}}$ are the amplitudes for the decays $B^0 \to f_{CP}$ and $\bar{B}^0 \to f_{CP}$.

The time dependent CP asymmetry

$$A(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$

where $B^0_{phys}(t)$ is the physical state at the time t resulting from the time evolution of a B^0 at time $t = 0$, can be written as

$$A(t) = Ccos(\Delta m_d\ t) + Ssin(\Delta m_d\ t) \tag{1}$$

where the coefficients C and S depend on λ.

In the case of the golden mode $B^0 \to J/\psi K^0_{S,L}$ the previous expressions simplify. As a single diagram is dominating the amplitude, no direct CP violation is expected, $|\lambda| = 1$ and

$$A_{J/\psi K^0_{S,L}}(t) = -\eta_{J/\psi K^0_{S,L}} sin(2\beta) sin(\Delta m_d\ t)$$

where β is one of the angles of the unitarity triangle.

Higher order diagrams are under excellent theoretical control. This mode has also the advantages of a clean experimental signature and a relatively high branching fraction ($\simeq 9\ 10^{-4}$).

4.2 Experimental technique

The analysis to measure the time dependent asymmetry relies on three basic steps:

- the exclusive reconstruction to isolate the final state $J/\psi K^0_{S,L}$;
- the vertexing to localize the decay point of both B produced from the $\Upsilon(4S)$;
- the flavor tagging, to determine whether the second B in the event decays as a B^0 or a $\bar{B}^0$.

Each of these steps can be checked by exclusively reconstructing a B meson decays in a flavor eigenstate, which yields a large data set called the flavor sample. This data set can be used for the measurement of the lifetime of the charged and neutral B meson and for the measurement of the $B-\bar{B}$ oscillation frequency Δm_d.

4.3 Exclusive reconstruction

In the golden channel $B^0 \to J/\psi K^0_S$ with $K^0_S \to \pi^+\pi^-$ 441 events have been reconstructed with 97 % purity. Other modes can be added like $B^0 \to J/\psi K^0_S$ with $K^0_S \to \pi^0\pi^0$, $B^0 \to \psi(2S)K^0_S$, $B^0 \to \chi_{c1}K^0_S$. Of particular interest is the mode $B^0 \to J/\psi K^0_L$ because it has the opposite CP parity. In this case the K^0_L is reconstructed from a neutral hadronic shower seen in the IFR detector.

The total CP sample consists of 803 tagged events with 80 % purity (fig. 1).

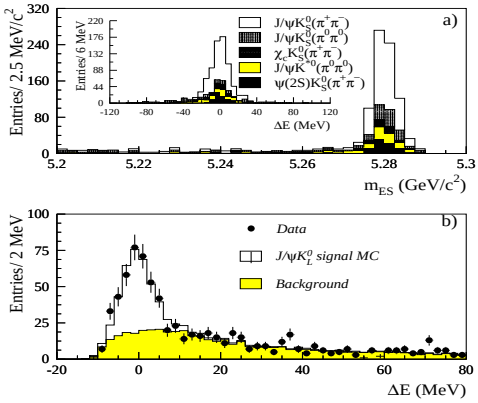

Figure 1: The upper plot show the invariant mass distribution for the sample with CP eigenvalue -1. ΔE, the difference between the energy of the candidate and the expected energy in the CM frame, is shown in the inset. The lower plot shows the ΔE distribution for the sample with CP eigenvalue +1 ($B^0 \to J/\psi K^0_L$). The total CP sample consists of 803 tagged events with 80 % purity.

4.4 Vertex reconstruction

The time difference between the decays of the two B meson can be reconstructed from the measured difference in the z coordinate of the two vertices: to an excellent accuracy $\Delta t = \Delta z/(\gamma\beta c)$ where $\gamma\beta$ is given by the boost of the $\Upsilon(4S)$ system which is essentially along the z coordinate.

The typical decay distance is 260 μm which needs to be compared to the experimental resolution of 180 μm. Therefore the resolution function plays a central role in this analysis.

4.5 Flavor Tagging

Each event with a CP candidate is assigned a B^0 or a $\bar{B}^0$ tag if the rest of the event satisfies the criteria from one of four tagging categories. Two tagging categories rely on the presence of a fast lepton or a charged kaon. Two other categories, called NT1 and NT2, are based on the output value of a neural network using other properties of the event (fast track, slow pion, etc.). The figure of merit for each tagging category is the effective tagging efficiency $Q = \epsilon(1-2w)^2$ where ϵ is the tagging efficiency and w is the fraction of events mistagged.

The performances of each tagging category (table 1) have been measured on a data sample where one of the B^0 meson has been reconstructed exclusively in a flavor eigenstate.

Table 1: Performances (in %) of the tagging algorithm measured on the data.

Tagging Cat.	ϵ	w	Q
Lepton	10.9 ± 0.3	8.9 ± 1.3	7.4 ± 0.5
Kaon	35.8 ± 0.5	17.6 ± 1.0	15.9 ± 0.9
NT1	7.8 ± 0.3	22.9 ± 2.1	2.5 ± 0.4
NT2	13.8 ± 0.3	35.1 ± 1.9	1.2 ± 0.3
All	68.4 ± 0.7	-	26.1 ± 1.2

4.6 Lifetime and Δm_d measurements

Applying the vertex reconstruction on a sample where one B meson has been exclusively reconstructed, it is possible to measure the lifetime of the charged and neutral B mesons. The results[4] $\tau_{B^0} = 1.546 \pm 0.032(stat) \pm 0.022(syst)\ ps$, $\tau_{B^+} = 1.673 \pm 0.032(stat) \pm 0.023(syst)\ ps$ and $\tau_{B^+}/\tau_{B^0} = 1.082 \pm 0.026(stat) \pm 0.011(syst)$, are in excellent agreement with the world average[5].

In order to measure the $B^0 - \bar{B}^0$ oscillation frequency Δm_d, a mixing asymmetry A_{mixing} can be defined as

$$A_{mixing}(\Delta t) = \frac{N(B^0\bar{B}^0) - N(B^0B^0 + \bar{B}^0\bar{B}^0)}{N(B^0\bar{B}^0) + N(B^0B^0 + \bar{B}^0\bar{B}^0)} \simeq (1-2w)cos(\Delta m_d \Delta t)$$

where the dilution factor $(1-2w)$ due to mistagging is equal to the dilution factor affecting the CP asymmetry. Figure 2 shows as a function of Δt the measured asymmetry for the flavor sample where the flavor tag has been applied on the other B meson in the event. The result of the fit

$$\Delta m_d = 0.519 \pm 0.020(stat) \pm 0.016(syst)\ \hbar\ ps^{-1}$$

is in agreement with the world average [5].

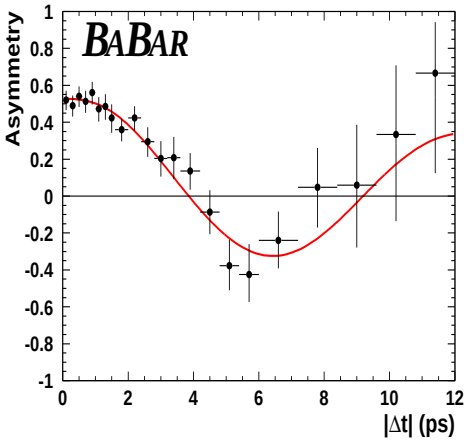

Figure 2: Asymmetry between unmixed and mixed final state, where one of the meson is reconstructed in a flavor eigenstate and the other is flavor tagged. The curve shows the result of the fit giving $\Delta m_d = 0.519 \pm 0.020(stat) \pm 0.016(syst)\ \hbar\ ps^{-1}$.

These two measurements prove that the analysis tools used for the CP analysis are well understood and can be used for very precise analysis.

4.7 The $\sin 2\beta$ *fit*

The time dependent CP asymmetry is defined as

$$A_{CP}(\Delta t) = \frac{N(B^0_{TAG}) - N(\bar{B}^0_{TAG})}{N(B^0_{TAG}) + N(\bar{B}^0_{TAG})}(\Delta t) \simeq (1-2w)sin(2\beta)sin(\Delta m_d \Delta t)$$

where $N(B^0_{TAG})$ is the number of events in the CP sample with the second B in the event tagged as a B^0.

The experimental distributions have been fitted using an unbinned maximum likelihood technique. The fit has been done simultaneously on the CP sample and on the flavor tagged sample, which is much larger and allows for a clean determination of the parameters describing the Δt resolution function and the flavor tagging performances.

The experimental distributions are presented on figure 3 and the result of the fit is [6]

$$\sin(2\beta) = 0.59 \pm 0.14(stat) \pm 0.05(syst).$$

This result establishes CP violation in the B^0 sector by more than 4 sigmas.

Many different crosschecks have been done and they show that this analysis method is not affected by a bias or other systematic effects beyond the quoted systematic uncertainty.

Figure 4 shows the constraint in the $\rho - \eta$ plane due to this measurement of $\sin(2\beta)$ together with all the other measurements of the unitarity triangle: there is a good agreement and obviously a precision measurement of $\sin(2\beta)$ will be a powerful probe of the Standard Model picture of CP violation.

Figure 5 presents this measurement together with the world measurements of $\sin(2\beta)$: the other most precise measurement comes from the KEK B factory experiment BELLE [7] and is in agreement with the result from BABAR.

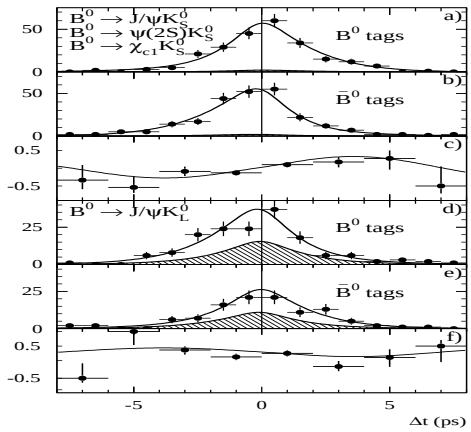

Figure 3: Δt distribution of events with B^0_{TAG} (a), $\bar{B}^0_{TAG}$ (b) and asymmetry (c) for the sample with CP eigenvalue -1. (d), (e) and (f), same for the sample with CP eigenvalue +1. The curves show the result of the fit and the hatched area corresponds to the background.

5 Studies of CP violation in charmless hadronic decays

The study of time dependent CP asymmetry for the $B^0 \to \pi^+\pi^-$ channel is particularly interesting because this analysis can give a measurement of the angle α of the unitarity triangle. In fact, if the tree diagram gave the dominant contribution to this process, the measured time dependent CP asymmetry could be simply expressed as $sin(2\alpha)sin(\Delta m_d \Delta t)$. However a large contribution from the Penguin diagrams is expected and this will make the extraction of α more difficult.

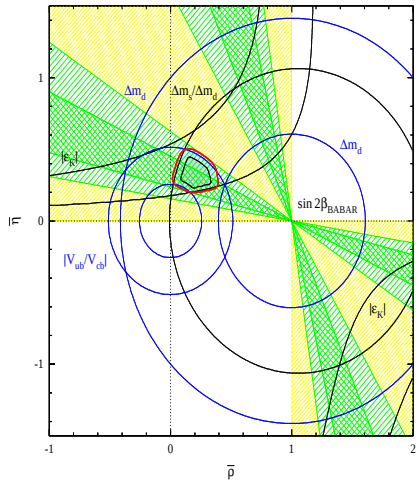

Figure 4: BABAR measurement of $\sin(2\beta)$ at the one and two sigma level (cross-hatched and hatched regions) and other constraints in the $\rho - \eta$ plane (solid lines). The shaded region corresponds to a global CKM fit not using the $\sin(2\beta)$ measurement. The BABAR result is in good agreement with the result of this fit.

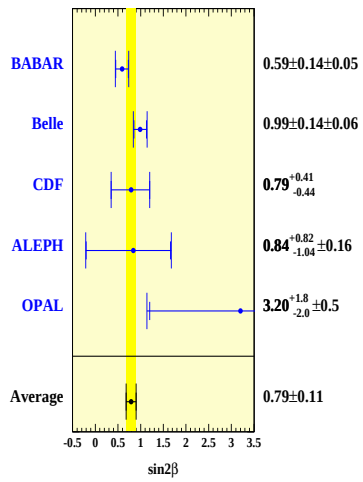

Figure 5: Measurements of $\sin(2\beta)$ and world average. The most precise measurements are from the B factories experiments BABAR and BELLE.

Experimentally this study is more difficult also because $B^0 \to K^+\pi^-$ and $B^0 \to K^+K^-$ decays may pollute the signal sample. In this case the DIRC detector allows to cleanly separate these decays. The measured yield is 65 ± 11 events in the $B^0 \to \pi^+\pi^-$ channel.

The time dependent asymmetry has been fit with a cosine and a sine term according to equation 1, and the results

$$S(\pi^+\pi^-) = 0.03^{+0.53}_{-0.56}(stat) \pm 0.11(syst) \quad (2)$$

$$C(\pi^+\pi^-) = -0.25^{+0.45}_{-0.47}(stat) \pm 0.14(syst) \quad (3)$$

have a large statistical error, so that more data will be needed for the observation of CP violation in this channel.

6 Direct CP violation study in radiative decays

Direct CP violation can be probed by studying the time independent CP asymmetry

$$A_D = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}$$

For the radiative decay $B \to K^*\gamma$ this asymmetry is expected to be very small in the Standard Model because only one amplitude contributes to this decay. Therefore this asymmetry constitutes an excellent window on new physics contributions.

The experimental result, based on a total yield of 139 events, is

$$A_D = -0.035 \pm 0.076(stat) \pm 0.012(syst),$$

so far consistent with no CP violation in this channel.

7 CP violation in mixing

CP violation in mixing occurs when the two neutral mass eigenstates are different from the CP eigenstates.

The time independent CP observable is

$$A_T = \frac{N(B^0B^0) - N(\bar{B}^0\bar{B}^0)}{N(B^0B^0) + N(\bar{B}^0\bar{B}^0)} \simeq \frac{4\epsilon_B}{1 + |\epsilon_B|^2}$$

where the last equality holds if CPT is conserved. The parameter ϵ_B plays a similar role as ϵ_K in the kaon system. In the Standard model A_T is expected to be 210^{-3}.

For this analysis direct semileptonic decays are used to flavor tag the B mesons and final states with two high energy leptons are selected. The measured asymmetry is then

$$A_T = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)}$$

The result

$$Re(\epsilon_B)/(1 + |\epsilon_B|^2) = +0.001 \pm 0.003(stat) \pm 0.004(syst)$$

is so far compatible with no CP violation.

Using the same experimental technique (events with two leptons in the final state) it is possible to define observables which compare B^0 and $\bar{B}^0$ decays and test the CPT symmetry. This analysis is in progress and preliminary results on CPT tests are expected soon.

8 Conclusions

PEP-II and BABAR had a fast and successful start recording a large $B\bar{B}$ sample with excellent data quality. Using this data sample the BABAR experiment has established CP violation in the B system by more than 4 sigmas and the measurement

$$\sin(2\beta) = 0.59 \pm 0.14(stat) \pm 0.05(syst)$$

provides already an interesting constraint in the $\rho - \eta$ plane of the unitarity triangle. The prospects are for a total integrated luminosity of 100 fb^{-1} by the summer 2002 and the expected error on $\sin(2\beta)$ ($\sin(2\alpha)$) should by then be below 0.1 (0.3). A rich variety of CKM measurements will be performed using these data.

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