Results from the current experiments: BaBar, Belle, CLEO

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Received: 8 Mar 2002 / Accepted: 1 Jul 2002 / Published online: 25 Sep 2002

Abstract. Year 2001 marks the first observation of $CP$ violation in the neutral $B$ meson system. The observations reported by BaBar and Belle are summarized. Also presented are results from CLEO, BaBar and Belle on search for direct $CP$ violation, measurements of radiative/electroweak penguin decays, and search for $D^0 - \bar{D}^0$ mixing.

1 Observation of $CP$ violation in the $B^0$ meson system

One of the major goals of two high luminosity electron-positron $B$ factory experiments, BaBar at PEPII and Belle at KEKB, is to establish $CP$ asymmetries in the $B$ meson system. Since the startup in May 1999 both accelerators have been performing remarkably. In July 2001, both experiments announced the observation of the first statistically significant signals for $CP$ violation in the neutral $B$ meson system.

The interference between the direct $B^0_d \rightarrow f_{CP}$ decay amplitude and the mixing-induced $B^0_d \rightarrow \bar{B}^0_d \rightarrow f_{CP}$ decay amplitude, where $f_{CP}$ is a $CP$ eigenstate to which both $B^0_d$ and $\bar{B}^0_d$ can decay, gives rise to an asymmetry in the time-dependent decay rate:

$$A(t) \equiv \frac{dN/dt(B^0_{t=0} \rightarrow f_{CP}) - dN/dt(\bar{B}^0_{t=0} \rightarrow \bar{f}_{CP})}{dN/dt(B^0_{t=0} \rightarrow f_{CP}) + dN/dt(\bar{B}^0_{t=0} \rightarrow \bar{f}_{CP})} = -\xi_f \sin 2\phi_1 \sin \Delta m_d t,$$

where $t$ is the proper time, $dN/dt(B^0_{t=0} \rightarrow f_{CP})$ is the decay rate for a $B^0(\bar{B}^0)$ produced at $t = 0$ to decay to $f_{CP}$ at time $t$, $\xi_f$ is a $CP$-eigenvalue of $f_{CP}$, $(\xi_f = -1$ for $J/\psi K_S, \psi(2S)K_S, \chi_{c1}K_S$ and $\eta_c K_S$, and $+1$ for $J/\psi K_L$), $\Delta m_d$ is the mass difference between two $B^0$ mass eigenstates, and $\phi_1$ is one of the three internal angles of the CKM Unitarity Triangle, defined as $\phi_1 \equiv \pi - \arg\left(\frac{V_{ts}V_{td}^*}{V_{cb}V_{cd}^*}\right)$.

In $\Upsilon(4S)$ decays, $B^0$ and $\bar{B}^0$ mesons are pair-produced and remain in a coherent p-wave state until one of them decays. The decay of one $B^0$ meson to a final state $f_1$ at time $t_1$ projects the accompanying $B^0$ meson onto an orthogonal state at that time; this meson then propagates in time and decays.

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to $f_2$ at time $t_2$. CP violations can be measured if one of $B$ mesons decays to a tagging state, $f_{tag}$, which distinguishes between $B^0$ and $\overline{B}^0$, at time $t_{tag}$ and the other decays to an $f_{CP}$ state at time $t_{CP}$. A time-dependent asymmetry, $A(\Delta t)$, which is obtained by replacing time $t$ in (3) with the proper time interval $\Delta t \equiv t_{CP} - t_{tag}$, can then be observed in $Y(4S)$ decays. Because the $B^0\overline{B}^0$ pair is produced nearly at rest in the $Y(4S)$ center of mass system (cms), $\Delta t$ can be determined from the distance between $f_{CP}$ and $f_{tag}$ decay vertices in the boost ($z$) direction, $z_{CP}$ and $z_{tag}$, and $\Delta t \sim \Delta z/\beta\gamma c$, where $\beta\gamma$ is a Lorentz boost factor of the $Y(4S)$ rest frame (0.56 at PEPII and 0.425 at KEKB).

This asymmetry is diluted by experimental factors including background from the reconstructed $f_{CP}$ states, the fraction of events where the flavor of the $B$ meson is incorrectly tagged ($\omega$), and the resolution of the decay vertex determination ($\Delta\tau_{res}$):

$$A_{\text{observed}} = \frac{1}{1+B/S}(1-2\omega)\Delta\tau_{res} A = DA.$$  \hspace{1cm} (2)

where $B/S$ is the ratio of background to signal and $D(<1)$ is the “dilution factor.” The statistical error of $\sin 2\phi_1$ is inversely proportional to $D$: $\delta \sin 2\phi_1 = \frac{1}{\sqrt{S+B}}$. The measurement of CP violation requires the reconstruction of $B^0 \rightarrow J/\psi K$ decays, the determination of the $b$-flavor of the accompanying (tagging) $B$ meson, the measurement of $\Delta t$, and a fit of the expected $\Delta t$ distribution to the measured distribution using an unbinned maximum likelihood method.

The BaBar collaboration obtained, using 32 million $B\overline{B}$ pairs collected in 1999–2001, a $f_{CP}$ sample consisting of $J/\psi K_S(\pi^+\pi^-)$, $J/\psi K_S(\pi^0\pi^0)$, $\chi_{c1} K_S(\pi^+\pi^-)$, $\psi(2S) K_S(\pi^+\pi^-)$ and $J/\psi K_L$ final states [2]. It contains a total of 1230 events with the estimated background of 200 events, resulting in a purity of 84%. Figure 1a shows the distribution of the beam-energy constrained mass $M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_T^B)^2}$ for candidates having a $K_S$ in the final states, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy and $p_T^B$ is the cms momentum of the B candidate. Figure 1b shows the distribution of $\Delta E \equiv E_{\text{beam}}^B - E_{\text{beam}}^{\text{res}}$ for $J/\psi K_L$ candidates, where $E_{\text{beam}}^B$ is the cms energy of the $B$ candidate. The Belle collaboration obtained a $f_{CP}$ sample of 1316 events with 282 background events (a purity of $\sim 80\%$) from their 1999-2001 data set corresponding to 29 fb$^{-1}$ [3]. They included $\eta_c K_S(\pi^+\pi^-)$ in addition to the modes mentioned above. Figure 2a shows the distribution of $M_{bc}$ for charmonium($\psi c$) plus $K_S$ final states, while Fig. 2b, shows the distribution of reconstructed cms momenta ($p_T^B$) of $J/\psi K_L$ candidates. For signal, the $p_T^B$ peaks around 0.34 GeV/c. Table 1 lists the effective tagging efficiency $\epsilon(1-2\omega)^2$, where $\epsilon$ is the tagging efficiency and $\omega$ is the probability of an incorrect flavor assignment, the resolution of the decay length measurement and the resolution of the proper time measurement for BaBar and Belle as well as CDF and ALEPH experiments. The proper time resolution of CDF and ALEPH is better than that of two $B$ factory experiments because Lorentz boost factor is larger for high energy experiments.

Figure 3 shows the $\Delta t$ distributions for $\xi_f = -1$ and $\xi_f = +1$ samples for BaBar data. Figure 4 shows the $\Delta t$ distributions for the $q\xi_f = +1$ (solid points)