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Mixing-induced CP asymmetry in semileptonic B-meson decays at BaBar

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I report results of a search for *CP* violation in $B^0\bar{B}^0$ mixing performed by the *BABAR* collaboration. A sample of about 6×10^6 $B^0 \to D^{*-}X\ell^+\nu$ decays is selected with a partial reconstruction method; kaon tagging is used to assess the flavor of the other B meson in the event. The *CP* violating asymmetry $\mathscr{A}_{CP} \equiv \frac{N(B^0B^0)-N(\bar{B}^0\bar{B}^0)}{N(B^0B^0)+N(\bar{B}^0\bar{B}^0)} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$, corresponds to $\delta_{CP} = 1-|q/p| = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$.

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The weak-Hamiltonian eigenstates for neutral B mesons are related to the flavor eigenstates of the strong interaction Hamiltonian by $|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$. The value of the ratio $|q/p|$ can be determined from the asymmetry between the two oscillation probabilities $\mathscr{P} = P(B^0 \to \bar{B}^0)$ and $\overline{\mathscr{P}} = P(\bar{B}^0 \to B^0)$ through $\mathscr{A}_{CP} = \frac{(\overline{\mathscr{P}}-\mathscr{P})}{(\overline{\mathscr{P}}+\mathscr{P})} = \frac{1-|q/p|^4}{1+|q/p|^4} \approx 2(1-|q/p|) = 2\delta_{CP}$. The Standard Model (SM) prediction is $\mathscr{A}_{CP} = -(4.0 \pm 0.6)\times 10^{-4}$ [2]. Any observation with the present experimental sensitivity ($\mathscr{O}(10^{-3})$) would therefore reveal physics beyond the SM.

Experiments measure $\mathscr{A}_{CP}$ from the dilepton asymmetry, $\mathscr{A}_{\ell\ell} = \frac{N(\ell^+\ell^+)-N(\ell^-\ell^-)}{N(\ell^+\ell^+)+N(\ell^-\ell^-)}$, where an ℓ^+ (ℓ^-) tags a B^0 ($\bar{B}^0$) meson, and ℓ refers either to an electron or a muon [3]. These measurements benefit from the large number of produced dilepton events. However, they rely on the use of control samples to subtract the charge-asymmetric background originating from hadrons wrongly identified as leptons or leptons from light hadron decays, and to compute the charge-dependent lepton identification asymmetry that may produce a false signal. The systematic uncertanties associated with the corrections for these effects constitute a severe limitation to the precision of the measurements.

I describe a measurement of $\mathscr{A}_{CP}(B^0)$ with a new technique [1]. B^0 mesons (hereafter called B_R; charge conjugation is implied) are selected from semileptonic $B^0 \to D^{*-}X\ell^+\nu$ events with a partial reconstruction of the $D^{*-} \to \pi^-\bar{D}^0$ decay [4]. The observed asymmetry between the number of events with an ℓ^+ versus an ℓ^- is:

$$A_\ell \approx \mathscr{A}_{r\ell} + \mathscr{A}_{CP}\chi_d, \tag{1}$$

where $\chi_d = 0.1862 \pm 0.0023$ [5] is the integrated mixing probability for B^0 mesons and $\mathscr{A}_{r\ell}$ is the detector-induced charge asymmetry in the B_R reconstruction.

The flavor of the other B^0 meson (labeled B_T) is tagged using events with a charged kaon (K_T). An event with a K^+ (K^-) usually arises from a state that decays as a B^0 ($\bar{B}^0$) meson. When mixing occurs, the ℓ and K_T have the same electric charge. The observed asymmetry in the rate of mixed events is:

$$A_T = \frac{N(\ell^+K_T^+)-N(\ell^-K_T^-)}{N(\ell^+K_T^+)+N(\ell^-K_T^-)} \approx \mathscr{A}_{r\ell} + \mathscr{A}_K + \mathscr{A}_{CP}, \tag{2}$$

where $\mathscr{A}_K$ is the detector charge asymmetry in kaon reconstruction. A kaon with the same charge as the ℓ might also arise from the Cabibbo-Favored (CF) decays of the D^0 meson produced with the lepton from the partially reconstructed side (K_R). The asymmetry observed for these events is:

$$A_R = \frac{N(\ell^+K_R^+)-N(\ell^-K_R^-)}{N(\ell^+K_R^+)+N(\ell^-K_R^-)} \approx \mathscr{A}_{r\ell} + \mathscr{A}_K + \mathscr{A}_{CP}\chi_d. \tag{3}$$

Eqs. 1, 2, and 3 are used to extract $\mathscr{A}_{CP}$ $\mathscr{A}_{r\ell}$, and $\mathscr{A}_K$.

The measurement is performed on events corresponding to an integrated luminosity of 425.7 fb^{-1} [7] collected by the *BABAR* detector [6] on the peak of the $\Upsilon(4S)$ resonance. A 45 fb^{-1} sample collected 40 MeV below the resonance ("off-peak") is used for background studies. A simulated sample of $B\bar{B}$ events [8] equivalent to approximately three times the data is also used.

Hadronic events are preselected using standard *BABAR* prescriptions. The B_R sample is selected by searching for combinations of a charged lepton ℓ^+ ($1.4 < p_\ell < 2.3$ GeV/c) and a low

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momentum pion π_s^- ($60 < p_{\pi_s^-} < 190$ MeV/c), with charge opposite to the lepton, arising from $D^{*-} \to \bar{D}^0\pi_s^-$ decay. The two tracks must be consistent with originating from a common vertex, which is constrained to the beam collision point in the plane transverse to the beam axis. Finally, p_ℓ, $p_{\pi_s^-}$, and the probability of the vertex fit are combined in a likelihood ratio variable (η) optimized to reject combinatorial $B\bar{B}$ events. If more than one candidate is found in the event, the one with the largest value of η is chosen.

The square of the unobserved neutrino mass is determined as: $\mathscr{M}_\nu^2 = (E_{\rm beam} - E_{D^*} - E_\ell)^2 - (\mathbf{p}_{D^*} + \mathbf{p}_\ell)^2$, by neglecting the momentum of the B^0 ($p_B \approx 340$ MeV/c) and identifying the B^0 energy with the beam energy $E_{\rm beam}$ in the e^+e^- center-of-mass frame; E_ℓ and $\mathbf{p}_\ell$ are the energy and momentum of the lepton and $\mathbf{p}_{D^*}$ is the estimated momentum of the D^*, computed by approximating the D^{*-} direction with that of the π_s^- and parametrizing the D^{*-} energy as a function of the π_s^- energy [10]. All B^0 semileptonic decays with $\mathscr{M}_\nu^2$ near zero are considered to be signal events, including $B^0 \to D^{*-}X^0\ell^+\nu_\ell$ (primary), $D^{*-}X^0\tau^+\nu_\tau,\ \tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau$ (cascade), and $D^{*-}h^+$ (misidentified), where $h = \pi, K$ is misidentified as a lepton. B^0 decays to flavor-insensitive CP eigenstates, $B^0 \to D^{*\pm}DX, D \to \ell^\mp X$, and $B^+ \to D^{*-}X^+\ell^+\nu_\ell$ accumulate at $\mathscr{M}_\nu^2 \sim 0$ and are called "peaking background". The uncorrelated background consists of continuum and combinatorial $B\bar{B}$ events.

Charged kaons in the momentum range $0.2 < p_K < 4$ GeV/c are identified with an average efficiency of about 85% and a ∼3% pion misidentification rate. The K production point, computed from the intersection of the K track and the beam spot, is used to determine the distance Δz between the ℓ^+ π_s^- and K vertex coordinates along the beam axis. Then the proper time difference Δt between the B_R and the B_T is computed in the "Lorentz boost approximation" [11], $\Delta t = \frac{\Delta z}{\beta\gamma}$, where $\beta\gamma = 0.56$ is the average boost of the $\Upsilon(4S)$ in the laboratory frame. Since the B mesons are not at rest in the $\Upsilon(4S)$ rest frame, and in addition the K is usually produced in the cascade process $B_T \to DX, D \to KY$, Δt is only an approximation of the actual proper time difference between the B_R and the B_T. Events for which the uncertainty $\sigma(\Delta t)$ exceeds 3 ps are rejected. This selection reduces to a negligible level the contamination from protons produced in the scattering of primary particles with the beam pipe or the detector material and wrongly identified as kaons, which would otherwise constitute a large charge-asymmetric source of background.

An event is defined as "mixed" if the K and the ℓ have the same electric charge and as "unmixed" otherwise. In about 20% of the cases, the K has the wrong charge correlation with respect to the B_T, and the event is wrongly defined (mistags).

About 95% of the K_R candidates have the same electric charge as the ℓ; they constitute 75% of the mixed event sample. Due to the small lifetime of the D^0 meson, the separation in space between the K_R and the $\ell\pi_s$ production points is much smaller than for K_T. Therefore, Δt is used as a first discriminant variable. Kaons in the K_R sample are usually emitted in the hemisphere opposite to the ℓ, while genuine K_T are produced randomly, so the cosine of the angle $\theta_{\ell K}$ between the ℓ and the K is also used. In about 20% of the cases, the events contain more than one K; most often both a K_T and a K_R candidate are found. As these two carry different information, multiple-candidate events are accepted. Studies performed on esembles of simulated samples of events show that this choice does not affect the statistical uncertainty.

The composition of the selected events is determined by fitting the $\mathscr{M}_\nu^2$ distribution in the interval $[-10, 2.5]$ GeV^2/c^4 with the sum of continuum, $B\bar{B}$ combinatorial, and $B\bar{B}$ peaking events,

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splitted into direct ($B^0 \to D^{*-}\ell^+\nu$), "D^{**}" ($B \to D^{*-}X^0\ell^+\nu_\ell$), cascade, hadrons wrongly identified as leptons, and CP eigenstates. The fraction of direct, D^{**}, and $B\bar{B}$ combinatorial background are determined in the fit, while the continuum contribution is fixed to the expectation from off-peak events, rescaled by the on-peak to off-peak luminosity ratio, and the rest (less than 2% of the total) to the level predicted by the simulation. Based on the assumption of isospin conservation, 66% of the D^{**} events are assigned to B^+ decays and the rest to B^0 decays. The measurement yields $(5.945 \pm 0.007) \times 10^6$ peaking events (see the plot on the left of Fig. 1). The result of the fit is used to compute the fractions of continuum, combinatorial, and peaking B^+ background, CP eigenstates, and B^0 signal in the sample, as a function of $\mathscr{M}_\nu^2$. The fit is repeated after dividing events into the four lepton categories ($e^\pm, \mu^\pm$) and eight tagged samples ($e^\pm K^\pm$, $\mu^\pm K^\pm$).

A binned four-dimensional fit to Δt (100 bins), $\sigma(\Delta t)(20)$, $\cos\theta_{\ell k}(4)$, and $p_K(5)$ is used to measure $\mathscr{A}_{CP}$. Following Ref. [12] and neglecting resolution effects, the Δt distributions for mixed signal events with a K_T are represented by the following expressions:

$$\mathscr{F}_{\bar{B}^0\bar{B}^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{p}{q}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) - \left(1-\left|\frac{p}{q}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) - \left|\frac{p}{q}\right|(b-c)\sin(\Delta m_d\Delta t)\right]\left|\frac{q}{p}\right|^2,$$

$$\mathscr{F}_{B^0B^0}(\Delta t) = \frac{\Gamma_0 e^{-\Gamma_0|\Delta t|}}{2(1+r'^2)}\left[\left(1+\left|\frac{q}{p}\right|^2 r'^2\right)\cosh(\Delta\Gamma\Delta t/2) - \left(1-\left|\frac{q}{p}\right|^2 r'^2\right)\cos(\Delta m_d\Delta t) + \left|\frac{q}{p}\right|(b+c)\sin(\Delta m_d\Delta t)\right]\left|\frac{p}{q}\right|^2,$$

where the first index of $\mathscr{F}$ refers to the flavor of the B_R and the second to the B_T, $\Gamma_0 = \tau_{B^0}^{-1}$ is the average width of the two B^0 mass eigenstates, Δm_d and $\Delta\Gamma$ are respectively their mass and width differences, the parameter r' results from the interference of CF and Doubly Cabibbo Suppressed (DCS) decays on the B_T side [12] and has a very small value ($\mathscr{O}(1\%)$), and b and c are two parameters expressing the CP violation arising from that interference. In the SM, $b = 2r'\sin(2\beta+\gamma)\cos\delta'$ and $c = -2r'\cos(2\beta+\gamma)\sin\delta'$, where β and γ are angles of the Unitary Triangle and δ' is a strong phase. The quantities Δm_d, τ_B^0, b, c, and $\sin(2\beta+\gamma)$ are left free in the fit. The value of $\Delta\Gamma$ is fixed to zero. Neglecting the tiny contribution from DCS decays, the main contribution to the asymmetry is time independent and due to the normalization factors of the two mixed terms.

When the K_T comes from the decay of the B^0 meson to a CP eigenstate (as, for example $B^0 \to D^{(*)}\bar{D}^{(*)}$ [5]), a different expression applies: $\mathscr{F}_{CPe}(\Delta t) = \frac{\Gamma_0}{4}e^{-\Gamma_0|\Delta t|}[1 \pm S\sin(\Delta m_d\Delta t) \pm C\cos(\Delta m_d\Delta t)]$, where the plus (minus) sign applies if the B_R decays as a B^0 ($\bar{B}^0$). The fraction of these events (about 1%) and the parameters S and C are fixed in the fits and are taken from simulation.

The Δt distribution for the decays of the B^+ mesons is parametrized by an exponential function, $\mathscr{F}_{B^+} = \Gamma_+ e^{-|\Gamma_+\Delta t|}$, where $\Gamma_+^{-1} = \tau_{B^+} = (1.641 \pm 0.008)$ ps.

The Δt distributions for K_T in $B\bar{B}$ events, $\mathscr{G}_i(\Delta t)$ result from the convolution of the theoretical ones with a resolution function. Different sets of parameters are used for peaking and for combinatorial background events.

The Δt distributions for K_R events, $\mathscr{G}_{K_R}(\Delta t)$, are obtained from a subsample of data containing fewer than 5% K_T decays. Background-subtracted histograms are used in the likelihood functions. As an alternative, the same selection is applied to the simulation and the simulated Δt distribution are corrected by the ratio of histograms from data and simulation. The $\cos\theta_{\ell K}$ shapes are obtained from the histograms of the simulated distributions for $B\bar{B}$ events.

The Δt distribution of continuum events is represented by a decaying exponential convolved with Gaussians parametrized by fitting simultaneously the off-peak data.

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The rate of events in each bin (j) and for each tagged sample is then expressed as the sum of the predicted contributions from peaking events, $B\bar{B}$ combinatorial, and continuum background. Accounting for mistags and K_R events, the peaking B^0 contributions to the same-sign samples are:

$$\mathscr{G}_{\ell^+K^+}(j) \;=\; (1+\mathscr{A}_{r\ell})(1+\mathscr{A}_K)\{(1-f^{++}_{K_R})[(1-\omega^+)\mathscr{G}_{B^0B^0}(j)+\omega^-\mathscr{G}_{B^0\bar{B}^0}(j)]+f^{++}_{K_R}(1-\omega'^+)\mathscr{G}_{K_R}(j)(1+\chi_d\mathscr{A}_{\ell\ell})\},$$
$$\mathscr{G}_{\ell^-K^-}(j) \;=\; (1-\mathscr{A}_{r\ell})(1-\mathscr{A}_K)\{(1-f^{--}_{K_R})[(1-\omega^-)\mathscr{G}_{\bar{B}^0\bar{B}^0}(j)+\omega^+\mathscr{G}_{\bar{B}^0B^0}(j)]+f^{--}_{K_R}(1-\omega'^-)\mathscr{G}_{K_R}(j)(1-\chi_d\mathscr{A}_{\ell\ell})\},$$

where the reconstruction asymmetries have separate values for the e and μ samples. Different mistag probabilities are used for K_T ($\omega^\pm$) and K_R ($\omega'^\pm$). The parameters $f^{\pm\pm}_{K_R}(p_k)$ describe the fractions of K_R tags in each sample as a function of the kaon momentum.

A total of 168 parameters are determined in the fit. A fit to the simulated events (analyzed as data) reproduces the generated values of δ_{CP} (zero) and of the other most significant parameters ($\mathscr{A}_{r\ell}$, $\mathscr{A}_K$, Δm_d, and τ^0_B). Sixtyseven different samples of simulated events with $\delta_{CP} = \pm0.005, \pm0.010, \pm0.025$ and $\mathscr{A}_{r\ell}$ or $\mathscr{A}_K$ varied in the range of $\pm10\%$ are produced by removing events. In each case, the input values are correctly determined, and an unbiased value of δ_{CP} is always obtained.

The fit to the data yields $\delta_{CP} = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$, where the first uncertainty is statistical and the second systematic. The values of the detector charge asymmetries are $\mathscr{A}_{r,e} = (3.0\pm0.4)\times10^{-3}$, $\mathscr{A}_{r,\mu} = (3.1\pm0.5)\times10^{-3}$, and $\mathscr{A}_K = (13.7\pm0.3)\times10^{-3}$. The frequency of the oscillation $\Delta m_d = 508.5\pm0.9$ ns $^{-1}$ is consistent with the world average, while $\tau_{B^0} = 1.553\pm0.002$ ps is somewhat larger than the world average, which is accounted for in the systematic uncertainties. The plots on Fig. 1 (right) show the fit projections for Δt for four tagged samples.

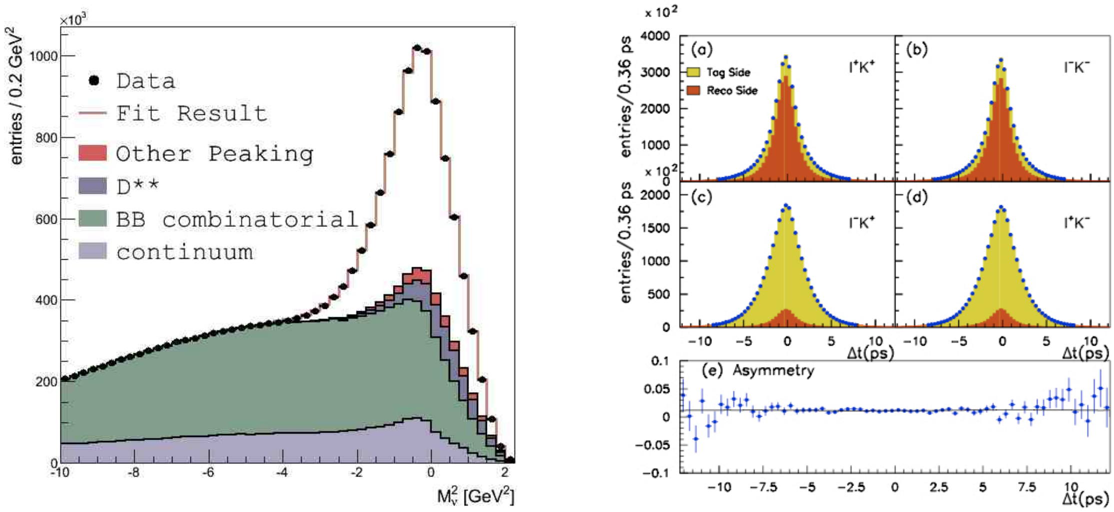

Figure 1: Left: $\mathscr{M}^2_\nu$ distribution for selected events. The data are represented by the points with error bars. The fitted contributions from $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$, other peaking background, D^{**} events, $B\bar{B}$ combinatorial background, and rescaled off-peak events are overlaid. Right: comparison between data and fit results along the Δt projection for unmixed B^0 (a), unmixed $\bar{B}^0$ (b), mixed B^0 (c), unmixed $\bar{B}^0$ (d). Plot (e) shows the asymmetry for mixed events as a function of Δt

The systematic uncertainty is computed as the sum in quadrature of several contributions, described below.

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The sample composition is varied by the statistical uncertainty of the $\mathscr{M}_\nu^2$ fit, the fraction of B^0 to B^+ in the D^{**} peaking sample in the range $50 \pm 25\%$ to account for possible violation of isospin symmetry, the fraction of the peaking contributions taken from the simulation by $\pm 20\%$, and the fraction of CP eigenstates by $\pm 50\%$. The fraction of B^+ events in the $B\bar{B}$ combinatorial sample is varied by the uncertainty in inclusive branching fraction for $B^0 \to D^{*-}X$, $\pm 4.5\%$. The ratio of $B^+ \to K_R X$ to $B^0 \to K_R X$ is varied by the uncertainty of the fraction $\frac{BR(D^{*0}\to K^- X)}{BR(D^{*+}\to K^- X)}$, $\pm 6.8\%$. The difference between the result when all resolution parameters are determined in the fit and those obtained when those that exhibit a weak correlation with $|q/p|$ are fixed is used to account for residual effects due to Δt resolution. The difference between the results obtained using the two different strategies to describe the K_R Δt distribution is added to the overall error. Parametrized simulations are used to check the estimate of the result and its statistical uncertainty. The statistical uncertainty on the validation test using the detailed simulation and the difference between the nominal result and the central result determined from the ensemble of parametrized simulations are added to the error. The S and C parameters describing the CP eigenstates are varied by their statistical uncertainties as obtained from simulation. The fit is repeated setting the value of $\Delta\Gamma$ to 0.02 ps^{-1}. The lifetimes of the B^0 and B^+ mesons and Δm_d are floated in the fit. The effect of fixing each parameter in turn to the world average is also considered.

In summary, I have described new measurement of the parameter governing CP violation in B^0 $\bar{B}^0$ oscillations. With a partial $B^0 \to D^{*-}X\ell^+\nu$ reconstruction and kaon tagging, *BABAR* finds $\delta_{CP} = (0.29 \pm 0.84^{+1.88}_{-1.61}) \times 10^{-3}$, and $\mathscr{A}_{CP} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$. These results are consistent with, and more precise than, dilepton-based results from B factories [3]. No deviation is observed from the SM expectation [2].

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