Measurements of *CP*-Violating Asymmetries in $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ Decays

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We present measurements of CP-violating asymmetries in the decay $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ with $a_1^{\pm}(1260) \to \pi^{\mp}\pi^{\pm}\pi^{\pm}$. The data sample corresponds to 384×10^6 $B\bar{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric B factory at SLAC. We measure the CP-violating asymmetry $\mathcal{A}_{CP}^{a_1\pi} = -0.07 \pm 0.07 \pm 0.02$, the mixing-induced CP violation parameter $S_{a_1\pi} = 0.37 \pm 0.21 \pm 0.07$, the direct

CP violation parameter $C_{a_1\pi} = -0.10 \pm 0.15 \pm 0.09$, and the parameters $\Delta C_{a_1\pi} = 0.26 \pm 0.15 \pm 0.07$ and $\Delta S_{a_1\pi} = -0.14 \pm 0.21 \pm 0.06$. From these measured quantities we determine the angle $\alpha_{\rm eff} = 78.6° \pm 7.3°$.

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The angle $\alpha \equiv \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$ of the unitarity triangle of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] has recently been measured by the *BABAR* and Belle Collaborations from time-dependent CP asymmetries in the B^0 decays to $\pi^+\pi^-$ [2], $\rho^\pm\pi^\mp$ [3], and $\rho^+\rho^-$ [4]. The decay B^0 to $a_1\pi$ [5] proceeds dominantly through the $\bar{b} \to \bar{u}u\bar{d}$ process in the same way as the previously studied modes [6,7]. However, due to the presence of additional loop contributions, these measurements determine an effective value $\alpha_{\rm eff}$, rather than α itself. This obstacle can be overcome using isospin symmetry [8], with bounds to $\Delta\alpha = \alpha - \alpha_{\rm eff}$ determined using either an isospin analysis [9] or broken SU(3) flavor symmetry [10]. Because it has the smallest contribution from loop diagrams, the $B^0 \to \rho^+\rho^-$ decay currently allows the most precise single determination of α [11]. The *BABAR* collaboration recently reported the observation of $B^0 \to a_1^\pm\pi^\mp$ [12]. The state $a_1^\pm\pi^\mp$, like $\rho^\pm\pi^\mp$, is not a CP eigenstate and four flavor-charge configurations must be considered [$B^0(\bar{B}^0) \to a_1^\pm\pi^\mp$]. Theoretical bounds on $\Delta\alpha$ in these decay modes based on SU(3) flavor symmetry have been derived in Ref. [7].

In this Letter we report measurements of the CP parameters in the decay $B^0 \to a_1^\pm\pi^\mp$ with $a_1^\pm \to \pi^\mp\pi^\pm\pi^\pm$. The analysis is done in the quasi-two-body approximation. Details on the reconstruction and handling of the a_1 meson can be found in Ref. [12]. The data were collected with the *BABAR* detector [13] at the PEP-II asymmetric e^+e^- collider. An integrated luminosity of 349 fb^{-1}, corresponding to $(384 \pm 4) \times 10^6$ $B\bar{B}$ pairs, was recorded near the $\Upsilon(4S)$ resonance ("on resonance") at a center-of-mass (c.m.) energy $\sqrt{s} = 10.58$ GeV. An additional 37 fb^{-1} were taken about 40 MeV below this energy ("off resonance") for the study of continuum background in which a charm or lighter quark pair is produced.

From a candidate $B\bar{B}$ pair we reconstruct a B^0 decaying into the final state $f = a_1\pi$ ($B^0_{a_1\pi}$). We also reconstruct the vertex of the other B meson ($B^0_{\rm tag}$) and identify its flavor. The difference $\Delta t \equiv t_{a_1\pi} - t_{\rm tag}$ of the proper decay times of the reconstructed and tag B mesons, respectively, is obtained from the measured distance between the $B^0_{a_1\pi}$ and $B^0_{\rm tag}$ decay vertices and from the boost ($\beta\gamma = 0.56$) of the e^+e^- system. The Δt distributions are given [7] by

$$F_{Q_{\rm tag}}^{a_1^\pm\pi^\mp}(\Delta t) = (1 \pm \mathcal{A}_{CP}^{a_1\pi})\frac{e^{-|\Delta t|/\tau}}{4\tau}\{1 - Q_{\rm tag}\Delta w + Q_{\rm tag}(1-2w)[(S_{a_1\pi} \pm \Delta S_{a_1\pi})\sin(\Delta m_d \Delta t) - (C_{a_1\pi} \pm \Delta C_{a_1\pi})\cos(\Delta m_d \Delta t)]\}, \quad (1)$$

where $Q_{\rm tag} = 1(-1)$ when the tagging meson $B^0_{\rm tag}$ is a $B^0(\bar{B}^0)$, τ is the mean B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a $\bar{B}^0$ or vice versa. The time- and flavor-integrated charge asymmetry $\mathcal{A}_{CP}^{a_1\pi}$ measures direct CP violation. The quantities $S_{a_1\pi}$ and $C_{a_1\pi}$ parametrize the mixing-induced CP violation related to the angle α, and flavor-dependent direct CP violation, respectively. The parameter $\Delta C_{a_1\pi}$ describes the asymmetry between the rates $\Gamma(B^0 \to a_1^+\pi^-) + \Gamma(\bar{B}^0 \to a_1^-\pi^+)$ and $\Gamma(B^0 \to a_1^-\pi^+) + \Gamma(\bar{B}^0 \to a_1^+\pi^-)$, while $\Delta S_{a_1\pi}$ is related to the strong phase difference between the amplitudes contributing to $B^0 \to a_1\pi$ decays. The parameters $\Delta C_{a_1\pi}$ and $\Delta S_{a_1\pi}$ are insensitive to CP violation. The flavor-tagging algorithm uses six mutually exclusive categories. Its analyzing power is measured to be $(30.4 \pm 0.3)\%$ [14].

Charged particles are detected and their momenta measured by the combination of a silicon vertex tracker (SVT), consisting of five layers of double-sided silicon detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. Charged-particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. Separation between pions and kaons is achieved at the level of 4 standard deviations (σ) for momenta below 3 GeV, decreasing to 2.5σ at 4 GeV.

Full Monte Carlo (MC) simulations [15] of the signal decay modes, continuum, and $B\bar{B}$ backgrounds are used to establish the event selection criteria. The MC signal events are simulated as B^0 decays to $a_1\pi$ with $a_1 \to \rho\pi$. For the a_1 meson parameters we take the mass $m_0 = 1230$ MeV and the width $\Gamma_0 = 400$ MeV [16,17].

We reconstruct the decay $a_1 \to 3\pi$ with the following requirement on the invariant mass: $0.87 < m_{a_1} < 1.8$ GeV. The intermediate dipion state is reconstructed with an invariant mass between 0.51 and 1.1 GeV. We impose several PID requirements to ensure the identity of the signal pions. For the decay pion coming from the B meson we require the measured Cherenkov angle to be within -2σ and $+5\sigma$ from the expected value for a pion. This requirement removes 98.6% of the background from a_1K. A B candidate is characterized kinematically by the energy-substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$, where the subscripts 0 and B refer to the initial $\Upsilon(4S)$ and to the B candidate in the laboratory frame, respectively, and the asterisk denotes the c.m. frame. The resolutions in $m_{\rm ES}$ and in ΔE are about 3.0 and 20 MeV, respectively. We require $|\Delta E| \leq 0.1$ GeV and $5.25 \leq m_{\rm ES} \leq 5.29$ GeV. To reduce the number of false B-meson candidates we require that the probability of the B vertex fit be greater than 0.01.

To reject continuum background, we use the angle θ_T between the thrust axis of the B candidate and that of the rest of the tracks and neutral clusters in the event, calculated in the center-of-mass frame. The distribution of $\cos\theta_T$ is sharply peaked near ± 1 for $q\bar{q}$ candidates, which have a jetlike topology, and is nearly uniform for the isotropic B-meson decays. We require $|\cos\theta_T| < 0.65$. The absolute value of the cosine of the angle between the direction of the π meson from $a_1 \rightarrow \rho\pi$ with respect to the flight direction of the B in the a_1 meson rest frame is required to be less than 0.85 to suppress combinatorial background. The distribution of this variable is uniform for signal and peaks near unity for this background. We discriminate further against $q\bar{q}$ background with a Fisher discriminant $\mathcal{F}$ that combines several variables that characterize the production dynamics and energy flow in the event [18]. The remaining continuum background is modeled from off-resonance data.

We use MC simulations of $B^0\bar{B}^0$ and B^+B^- decays to look for $B\bar{B}$ backgrounds, which can come from B decays with or without charmed particles in the final state. Neutral and charged D mesons may contribute to background through particle misidentification or misreconstruction. We remove any combinations of the decay products, including possible additional π^0, with invariant mass consistent with nominal mass values for $D^\pm \rightarrow K^\mp\pi^\pm\pi^\pm$ or $K_S^0\pi^\pm$ and $D^0 \rightarrow K^\mp\pi^\pm$ or $K^\mp\pi^\pm\pi^0$. The decay mode $B^0 \rightarrow a_2^\pm(1320)\pi^\mp$ has the same final-state particles as the signal. We suppress this decay with the angular variable $\mathcal{H}$, defined as the cosine of the angle between the normal to the plane of the 3π resonance and the flight direction of the primary pion from B meson evaluated in the 3π resonance rest frame. Since the a_1 and $a_2(1320)$ mesons have spins of 1 and 2, respectively, the distributions of the variable $\mathcal{H}$ for these two resonances differ. We require $|\mathcal{H}| < 0.62$.

We obtain the CP parameters and signal yield from an unbinned extended maximum likelihood (ML) fit with the input observables ΔE, $m_{\rm ES}$, $\mathcal{F}$, m_{a_1}, $\mathcal{H}$, and Δt. We have six fit components in the likelihood: signal, charm and charmless $B\bar{B}$ background, $B^0 \rightarrow a_2^\pm(1320)\pi^\mp$, continuum $q\bar{q}$ background, and nonresonant $\rho\pi\pi$. The charmless component also includes candidates that were incorrectly reconstructed from particles in events that contain a true signal candidate. Based on measurements of branching fractions for similar charmless decays, we assume $\mathcal{B}(B^0 \rightarrow \rho^0\pi^+\pi^-) = (2 \pm 2) \times 10^{-6}$ [19], which corresponds to 19 expected events in the ML fit sample. This yield is fixed in the fit and a systematic uncertainty is assigned to the final results.

The total probability density function (PDF) for the component j and tagging category c in the event i, $\mathcal{P}^i_{j,c}$, is written as a product of the PDFs of the discriminating variables used in the fit. The factored form of the PDF is a good approximation since linear correlations among observables are below 10%. The systematic uncertainty from residual correlations is taken into account in the fit bias. We write the extended likelihood function for all events as

$$\mathcal{L} = \prod_c \exp(-n_c) \prod_i^{N_c} \Big[\sum_j n_j f_{j,c} \mathcal{P}^i_{j,c} \Big], \tag{2}$$

where n_j is the yield of events of component j, $f_{j,c}$ is the fraction of events of component j for each category c, $n_c = \sum_j f_{j,c} n_j$ is the number of events found by the fit for category c, and N_c is the number of events of category c in the sample. We fix $f_{j,c}$ to $f_{B_{\rm flav},c}$, the values measured with a large sample of fully reconstructed B^0 decays into flavor eigenstates ($B_{\rm flav}$ sample) [20], for the signal, $\rho\pi\pi$, and $B^0 \rightarrow a_2^\pm(1320)\pi^\mp$ fit components. We fix $f_{j,c}$ to values obtained with MC events for the charmless and charm fit components and allow it to vary for the $q\bar{q}$ component.

The PDF $\mathcal{P}_{\rm sig}(\Delta t, \sigma_{\Delta t}; c)$, for each category c, is the convolution of $F(\Delta t; c)$ [Eq. (1)] with the signal resolution function (sum of three Gaussians) determined from the $B_{\rm flav}$ sample. The Δt resolution functions for all the other fit components are also modeled with the sum of three Gaussians. For charmless, $B^0 \rightarrow a_2^\pm(1320)\pi^\mp$, and $\rho\pi\pi$ components in the nominal fit to the data we assume $S = 0$, $C = 0$, $\Delta S = 0$, and $\Delta C = 0$, and we vary these parameters when evaluating systematic uncertainties on final results. We use an effective B lifetime for the charmless component as obtained from a fit to MC signal events. The continuum (charm) Δt distributions are parametrized as sums of three Gaussians with parameters determined from a fit to off-resonance (MC) events.

The PDF of the invariant mass of the a_1 meson in signal events is parametrized as a relativistic Breit-Wigner line shape with a mass-dependent width that takes into account the effect of the mass-dependent ρ width [21]. The PDF of the invariant mass of the $a_2(1320)$ meson is parametrized as a relativistic Briet-Wigner function. The $m_{\rm ES}$ and ΔE distributions for signal are parametrized as a sum of two Gaussian distributions. The ΔE distribution for continuum background is parametrized by a linear function, and the combinatorial background in $m_{\rm ES}$ is described by a phase-space-motivated empirical function [22]. We model the Fisher distribution $\mathcal{F}$ using a Gaussian function with different widths above and below the mean. The $\mathcal{A}$ distributions are modeled using polynomials.

The PDF parameters are determined from MC simulated events with the exception of the continuum background, where we use off-resonance data, and of the signal resolution function, where we use the $B_{\rm flav}$ sample. Large data control samples of B decays to charmed final states of similar topology are used to verify the simulated resolutions in $m_{\rm ES}$ and ΔE. Where the control samples reveal differences between data and MC samples in mass and energy resolution, we shift or scale the resolution used in the likelihood fits.

We test and calibrate the fitting procedure by applying it to ensembles of simulated $q\bar{q}$ experiments drawn from the PDF, into which we have embedded the expected number of signal, charmless, $B^0 \to a_2^{\pm}(1320)\pi^{\mp}$, the charm, and the $\rho\pi\pi$ events randomly extracted from the fully simulated MC samples. The measured quantities $S_{a_1\pi}$, $C_{a_1\pi}$, $\Delta S_{a_1\pi}$, $\Delta C_{a_1\pi}$, and $\mathcal{A}_{CP}^{a_1\pi}$ have been corrected for the fit biases, and a systematic uncertainty equal to half of the bias found in MC simulations is assigned on the final results.

In the fit there are 35 free parameters, including $S_{a_1\pi}$, $C_{a_1\pi}$, $\Delta S_{a_1\pi}$, $\Delta C_{a_1\pi}$, the charge asymmetries for signal and continuum background, five yields, the signal a_1 width, eleven parameters determining the shape of the combinatorial background, and 12 tagging efficiencies for the continuum. The main contributions to the systematic error on the signal parameters are summarized in Table I. We have studied systematic uncertainties arising from several sources: variation of the signal PDF shape parameters within their errors; modeling of the signal Δt distribution; tagging efficiency and mistag rates determined from the $B_{\rm flav}$ sample [20]; uncertainties in Δm_d and τ [16]; uncertainty in fit bias; uncertainty due to CP violation present in the $B\bar{B}$ background, the $a_2^{\pm}(1320)\pi^{\mp}$ CP violation; uncertainty due to the interference between $B^0 \to a_1^{\pm}\pi^{\mp}$ and other 4π final states have been estimated with MC simulations; doubly Cabibbo-suppressed (DCS) $b \to \bar{u}c\bar{d}$ amplitude for some tagside B decays [23]; SVT alignment; and the particle identification algorithm. Systematic uncertainties due to neglected minor a_1 substructures are negligible. We allow for a CP asymmetry up to 20% in B decays to charmless final states, and up to 50% in B decays to $a_2(1320)\pi$.

TABLE I. Summary of the systematic uncertainties (in units of 10^{-2}).

	$S_{a_1\pi}$	$C_{a_1\pi}$	$\Delta S_{a_1\pi}$	$\Delta C_{a_1\pi}$	$\mathcal{A}_{CP}^{a_1\pi}$
PDF parametrization	4.8	5.3	3.3	5.3	1.5
Signal Δt model	0.2	0.2	0.3	0.1	0.0
Tagging and mistag	0.3	0.2	0.2	0.4	0.1
Δm_d and τ	0.0	0.2	0.3	0.1	0.0
Fit bias	0.8	0.2	0.8	1.0	0.3
$B\bar{B}$ CP violation	4.1	4.3	4.2	4.0	0.5
$a_2^{\pm}(1320)\pi^{\mp}$ + interf.	2.8	4.5	3.2	0.6	0.2
DCS decays	0.8	2.2	0.0	2.2	0.1
SVT alignment	1.0	0.6	1.0	0.6	0.0
Particle ID	0.1	0.1	0.1	0.1	0.2
Total	7.0	8.5	6.4	7.1	1.6

From the fit to a sample of 29 300 events, we obtain a signal yield of 608 ± 52 (461 ± 46 have their flavor identified) used to measure the following parameters: $S_{a_1\pi} = 0.37 \pm 0.21 \pm 0.07$, $\Delta S_{a_1\pi} = -0.14 \pm 0.21 \pm 0.06$, $C_{a_1\pi} = -0.10 \pm 0.15 \pm 0.09$, $\Delta C_{a_1\pi} = 0.26 \pm 0.15 \pm 0.07$, $\mathcal{A}_{CP}^{a_1\pi} = -0.07 \pm 0.07 \pm 0.02$. Linear correlations between these fit parameters are small.

The angle $\alpha_{\rm eff}$ can be defined [7] as

$$\alpha_{\rm eff} = \frac{1}{4}\left[\arcsin\left(\frac{S_{a_1\pi} + \Delta S_{a_1\pi}}{\sqrt{1 - (C_{a_1\pi} + \Delta C_{a_1\pi})^2}}\right) + \arcsin\left(\frac{S_{a_1\pi} + \Delta S_{a_1\pi}}{\sqrt{1 - (C_{a_1\pi} - \Delta C_{a_1\pi})^2}}\right)\right]. \quad (3)$$

Using the measured parameters in this formula, the angle $\alpha_{\rm eff}$ can be extracted up to a 16-fold ambiguity, which can be reduced to a fourfold ambiguity with conservative assumptions based on factorization [7,10]. One of the four solutions, $\alpha_{\rm eff} = 78.6° \pm 7.3°$, is compatible with the result of standard model [1] based fits. We also determine the two direct CP asymmetries [24] $\mathcal{A}_{a_1\pi}^{+-} = 0.15 \pm 0.16$ and $\mathcal{A}_{a_1\pi}^{-+} = 0.07 \pm 0.25$ and their linear correlation 0.63. Using the published branching fraction [12], we obtain also the following values for the flavor-charge branching fractions [24] (in units of 10^{-6}): $\mathcal{B}(B^0 \to a_1^+\pi^-) = 17.9 \pm 4.8$, $\mathcal{B}(B^0 \to a_1^-\pi^+) = 11.4 \pm 4.7$, $\mathcal{B}(\bar{B}^0 \to a_1^+\pi^-) = 13.0 \pm 4.3$, and $\mathcal{B}(\bar{B}^0 \to a_1^-\pi^+) = 24.2 \pm 5.8$. The errors are obtained adding in quadrature statistical and systematic errors.

Figure 1 shows distributions of $m_{\rm ES}$ and ΔE, enhanced in signal content by requirements on the signal-to-continuum likelihood ratios using all discriminating variables other than the one plotted. Figure 2 gives the Δt projections and asymmetry for flavor tagged events.

In summary, we have measured the CP-violating asymmetries in $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ decays and determined the angle $\alpha_{\rm eff}$. We do not find evidence for direct or mixing-induced CP violation in these decays. Once measurements

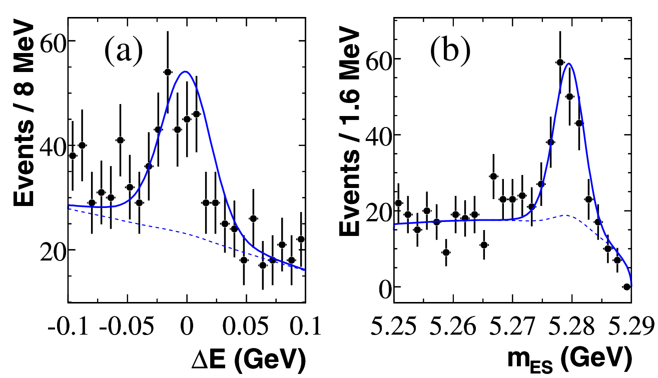

FIG. 1 (color online). Projections of (a) ΔE, (b) $m_{\rm ES}$. Points represent on-resonance data, dotted lines the sum of all backgrounds, and solid lines the full fit function. These plots are made with a cut on the signal likelihood.

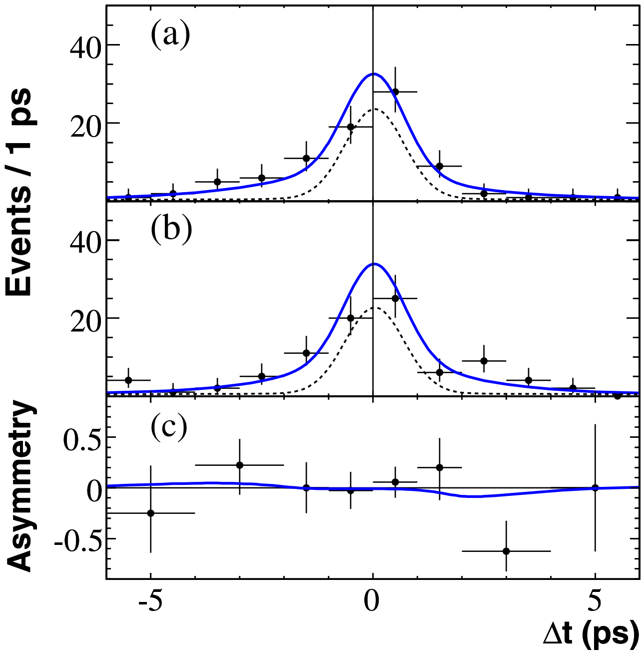

FIG. 2 (color online). Projections onto Δt of the data (points) for (a) B^0 and (b) $\bar{B}^0$ tags, showing the fit function (solid line), and the background function (dotted line), and (c) the asymmetry between B^0 and $\bar{B}^0$ tags.

of branching fractions for SU(3)-related decays become available, quantitative bounds on $\Delta\alpha$ obtained with the method of Ref. [7] will provide significant constraints on the angle α through the measurement of $\alpha_{\rm eff}$ in $B^0 \to a_1^{\pm}(1260)\pi^{\mp}$ decays.

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