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Evidence for *CP* violation in $B^0 \to J/\psi\,\pi^0$ decays

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We present measurements of the branching fraction and time-dependent CP asymmetries in $B^0 \to J/\psi\,\pi^0$ decays based on 466 million $\Upsilon(4S) \to B\overline{B}$ events collected with the BABAR detector at the SLAC PEP-II asymmetric-energy B factory. We measure the CP asymmetry parameters $S = -1.23 \pm 0.21(\text{stat}) \pm 0.04(\text{syst})$ and $C = -0.20 \pm 0.19(\text{stat}) \pm 0.03(\text{syst})$, where the measured value of (S, C) is 4.0 standard deviations from $(0, 0)$ including systematic uncertainties. The branching fraction is determined to be $\mathcal{B}(B^0 \to J/\psi\,\pi^0) = (1.69 \pm 0.14(\text{stat}) \pm 0.07(\text{syst})) \times 10^{-5}$.

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Charge conjugation-parity (CP) violation in the B meson system has been established by the BABAR [1] and Belle [2] collaborations. The Standard Model (SM) of electroweak interactions describes CP violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. Measurements of CP asymmetries in the proper-time distribution of neutral B decays to CP eigenstates containing a J/ψ and K^0 meson provide a precise measurement of $\sin 2\beta$ [4], where β is $\arg\left[-V_{\rm cd}V_{\rm cb}^*/V_{\rm td}V_{\rm tb}^*\right]$ and the $V_{\rm ij}$ are CKM matrix elements with i, j quark indices.

The decay $B^0 \rightarrow J/\psi\pi^0$ is a Cabibbo-suppressed $b \rightarrow c\overline{c}d$ transition to a CP-even final state whose tree amplitude has the same weak phase as the $b \rightarrow c\overline{c}s$ modes, *e.g.*, the decay $B^0 \rightarrow J/\psi K^0_S$. The $b \rightarrow c\overline{c}d$ loop (penguin) amplitudes have different weak phases than the tree amplitude. If there is a significant penguin amplitude in $B^0 \rightarrow J/\psi\pi^0$, then the measured values of the CP asymmetry coefficients S and C will differ from the tree level expectations of $-\sin 2\beta$ and 0, respectively, and this mode could be sensitive to physics beyond the SM [5]. The coefficient S is related to CP violation in interference between amplitudes of direct decay, and decay after mixing, and C is related to direct CP violation. An additional motivation for measuring S and C from $B^0 \rightarrow J/\psi\pi^0$ is that they can provide a model-independent constraint on the penguin contamination within $B^0 \rightarrow J/\psi K^0_S$ [6].

The data used in this analysis were collected with the BABAR detector [7] at the PEP-II asymmetric e^+e^- storage ring [8]. This represents an integrated luminosity of 425 fb^{-1} collected on the $\Upsilon(4S)$ resonance (on-peak), which corresponds to (466 ± 5) million $B\overline{B}$ pairs. In this letter, we present an update of our previous measurements of the branching fraction $\mathcal{B}$ and CP asymmetries of $B^0 \rightarrow J/\psi\pi^0$ [9], which had been performed using an integrated luminosity of 232 fb^{-1}. Belle has also studied this mode and has published a branching fraction and a time-dependent CP violating asymmetry result using 29.4 fb^{-1} and 484.3 fb^{-1} of integrated luminosity, respectively [10, 11].

We reconstruct $B^0 \rightarrow J/\psi\pi^0$ decays from combinations of $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) and $\pi^0 \rightarrow \gamma\gamma$ candidates. A detailed description of the charged particle reconstruction and identification can be found elsewhere [12]. For the $J/\psi \rightarrow e^+e^-$ ($\mu^+\mu^-$) channel, the invariant mass of the lepton pair is required to lie between 3.06 and 3.12 GeV/c^2 (3.07 and 3.13 GeV/c^2). Each lepton candidate must be consistent with the electron (muon) signature in the detector. We form $\pi^0 \rightarrow \gamma\gamma$ candidates from clusters in the electromagnetic calorimeter with an invariant mass, $m_{\gamma\gamma}$, satisfying $100 < m_{\gamma\gamma} < 160$ MeV/c^2. These clusters are required to be isolated from any charged tracks, carry a minimum energy of 30 MeV, and have a lateral energy distribution consistent with that of a photon. Each π^0 candidate is required to have a minimum energy of 200 MeV and is constrained to the nominal mass [13].

We use two kinematic variables, $m_{\rm ES}$ and ΔE, in order to isolate the signal: $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$ is the beam-energy substituted mass and $\Delta E = E_B^* - \sqrt{s}/2$ is the difference between the B-candidate energy and the beam energy. Here the $B^0 \rightarrow J/\psi\pi^0$ candidate ($B_{\rm rec}$) momentum $\mathbf{p}_B$ and four-momentum of the initial state ($E_i, \mathbf{p}_i$) are defined in the laboratory frame, E_B^* is the $B_{\rm rec}$ energy in the center-of-mass (CM) frame, and $\sqrt{s}/2$ is the beam energy in the CM frame. We require $m_{\rm ES} > 5.2\,{\rm GeV}/c^2$ and $-0.1 < \Delta E < 0.3\,{\rm GeV}$. The asymmetric ΔE cut is used in order to reduce background from B meson decays to final states including a J/ψ meson, where one or more of the particles in the final state is not reconstructed as part of $B_{\rm rec}$.

A significant source of background is from $e^+e^- \rightarrow q\overline{q}$ ($q = u, d, s, c$) continuum events. We combine several kinematic and topological variables into a Fisher discriminant ($\mathcal{F}$) to provide additional separation between signal and continuum. The three variables $\cos(\theta_H)$, L_0, and L_2 are inputs to $\mathcal{F}$, where θ_H is the angle between the positively charged lepton and the B candidate momenta in the J/ψ rest frame. The variables L_0 and L_2 are the zeroth- and second-order moments; $L_0 = \sum_i |\mathbf{p}_i^*|$ and $L_2 = \sum_i |\mathbf{p}_i^*|\,(3\cos^2\theta_i - 1)/2$, where $\mathbf{p}_i^*$ are the CM momenta of the tracks and neutral calorimeter clusters that are not associated with the signal candidate. The θ_i are the angles between $\mathbf{p}_i^*$ and the thrust axis of the signal candidate. We use data collected 40 MeV below the $\Upsilon(4S)$ resonance to model background from continuum events, and signal Monte Carlo (MC) simulated data to calculate the coefficients used in $\mathcal{F}$.

We use multivariate algorithms to identify signatures that determine (tag) the flavor of the decay of the other B in the event ($B_{\rm tag}$) to be either a B^0 or $\overline{B}^0$. The flavor tagging algorithm has seven mutually exclusive categories of events and is described in detail elsewhere [14]. The total effective tagging efficiency of this algorithm is given by $\sum_i \epsilon_i(1-2\omega_i)^2 = (30.5 \pm 0.4)\%$, where ϵ_i is the efficiency of a tag, ω_i is the probability of mis-identifying a tag, and i runs over the seven tag categories.

The decay rate f_+ (f_-) of neutral decays to a CP eigenstate, when $B_{\rm tag}$ is a B^0 ($\overline{B}^0$), is:

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \quad (1)$$

where Δt is the difference between the proper decay times of the $B_{\rm rec}$ and $B_{\rm tag}$ mesons, $\tau_{B^0} = 1.530 \pm 0.009$ ps is the B^0 lifetime and $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} is the B^0-$\overline{B}^0$ oscillation angular frequency [13]. The decay width difference between the B^0 mass eigenstates is assumed to be zero.

The time interval Δt is calculated from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and

$B_{\rm tag}$ along the collision axis (z). The vertex of $B_{\rm rec}$ is reconstructed from the lepton tracks that come from the J/ψ; the vertex of $B_{\rm tag}$ is constructed from tracks in the event that do not belong to $B_{\rm rec}$, with constraints from the beam spot location and the $B_{\rm rec}$ momentum. We accept events with $|\Delta t| < 20$ ps whose uncertainty $\sigma(\Delta t)$ is less than 2.5 ps.

After the selection criteria mentioned above are applied, the average number of candidates per event is approximately 1.1 in data. The multiple candidates per event result from having more than one choice of π^0 per event, so we choose the one whose value of $m_{\gamma\gamma}$ is closest to the π^0 mass reported by the PDG [13]. Overall, the true signal candidate is correctly identified 99.6% of the time for signal MC simulated data. After this step, the signal efficiency is 19.3% and a total of 1120 events are selected in on-peak data.

In addition to signal and continuum background events, there are also $B\overline{B}$-associated backgrounds present in the data. We consider B backgrounds from the following types of event: (i) $B^0 \to J/\psi K^0_S$, (ii) $B^0 \to J/\psi K^{*0}$, (iii) $B^\pm \to J/\psi K^{*\pm}$, (iv) $B^\pm \to J/\psi \rho^\pm$, (v) $B^0 \to J/\psi \rho^0$, (vi) other B decays to final states including a real J/ψ where the π^0 either comes from the other B in the event or is the decay product of particles produced in a $B \to J/\psi X$ decay, and (vii) B meson decays to final states including charm mesons, where the J/ψ is either real and comes from a $\psi(2S)$ or χ_{c1} decay, or it is fake, and the result of two semileptonic B decays where the invariant dilepton mass falls into the allowed window. The yields of these backgrounds are fixed to expectations (16.2, 9.4, 8.8, 2.3, 0.3, 79.4, and 60.4 events, respectively), using branching ratios from world averages [15]. We allow these to vary in turn when evaluating systematic uncertainties. Backgrounds from other B decays are small, and have been neglected.

The signal yield, S, and C are simultaneously extracted from an unbinned extended maximum-likelihood (ML) fit to the on-peak data sample, where the discriminating variables used in the fit are $m_{\rm ES}$, ΔE, $\mathcal{F}$ and Δt. For each candidate-type (signal, continuum, and the aforementioned B backgrounds) we construct a probability density function (PDF) that is the product of PDFs in each of these variables, assuming that they are uncorrelated. These combined PDFs are used in the fit to the data sample. The continuum-background $m_{\rm ES}$, ΔE, $\mathcal{F}$, and Δt PDF parameters are floated in the final fit to the data. For all other types the PDF parameters are extracted from high-statistics MC samples. The $m_{\rm ES}$ distributions for signal and $B^0 \to J/\psi K^0_S$ events peak at the B mass, and are described by a Gaussian with a low side exponential tail (GE). The $m_{\rm ES}$ PDFs for all other backgrounds are described by ARGUS functions [16]. The signal ΔE distribution is described by a sum of a GE distribution and a second order polynomial. We use a smoothed histogram of MC simulated data to describe the ΔE PDFs for $B^0 \to J/\psi K^0_S$, $B^\pm \to J/\psi \rho^\pm$, and B meson decays to final states including charm mesons, and second order polynomials for the ΔE PDFs of all other backgrounds. We parameterize the $\mathcal{F}$ distribution for signal and continuum events using the sum of a Gaussian and a Gaussian with different widths above, and below the mean. The $\mathcal{F}$ distributions for all other background PDFs are Gaussians. The signal Δt distribution is described by Eq. (1) convolved with three Gaussians (core, tail, outliers) which takes into account $\sigma(\Delta t)$ from the vertex fit, and tagging dilution. The resolution is parameterized using a large sample of fully reconstructed hadronic B decays [14]. The nominal Δt distribution for the B backgrounds is the same as for signal, except for inclusive B and $J/\psi K^{*0}$ backgrounds. As the Δt distributions for inclusive B and $J/\psi K^{*0}$ backgrounds are narrower than those of the signal and other B backgrounds, we use the lifetime obtained by fitting samples of MC of these modes. The fitted lifetime is 1.1 ps, which is an effective parameter, as opposed to having any physical meaning. The continuum background Δt distribution is described by the sum of three Gaussian distributions. The Δt PDF parameters depend on the flavor tag category. The signal yield is fitted using known tag efficiencies listed in Ref. [14] for each tag category. The continuum yields for the seven tagging categories are allowed to vary in the ML fit, and the fractions of B background events in each category are determined from MC samples.

After performing tests on the fitting procedure as described in Ref. [17], we fit the data. The results, corrected for fit bias (see below), are 184 ± 15(stat) signal events, $S = -1.23 \pm 0.21$(stat) and $C = -0.20 \pm 0.19$(stat). Figure 1 shows distributions of $m_{\rm ES}$, ΔE, and $\mathcal{F}$ for the data, where the signal is enhanced by selecting $\Delta E < 0.1$ GeV for the $m_{\rm ES}$ distribution, and $m_{\rm ES} > 5.275\,{\rm GeV}/c^2$ for the other distributions. These requirements have a relative signal efficiency of 98.8% (92.3%) and background efficiency of 64% (10.4%) for $m_{\rm ES}$ (ΔE and $\mathcal{F}$). Figure 2 shows the Δt distributions for signal B^0 and $\overline{B}^0$ tagged events. The signal is enhanced by excluding events from the tagging category with the largest value of ω, and by requiring $m_{\rm ES} > 5.275\,{\rm GeV}/c^2$ and $\Delta E < 0.1$ GeV. These requirements have a relative efficiency of 70.0% (4.4%) for signal (background). The time-dependent decay rate asymmetry $[N(\Delta t) - \overline{N}(\Delta t)]/[N(\Delta t) + \overline{N}(\Delta t)]$ is also shown, where N ($\overline{N}$) is the decay rate for B^0 ($\overline{B}^0$) tagged events.

Table I summarizes the systematic uncertainties on the signal yield, S, and C. These include the uncertainty due to the PDF parameterization (including the resolution function), evaluated by varying the signal and background PDF parameters within the uncertainties of their nominal values. The PDF parameter uncertainties are determined from MC samples of signal and background events. The uncertainties associated with the Lorentz boost, the z-scale of the tracking system, and the event-

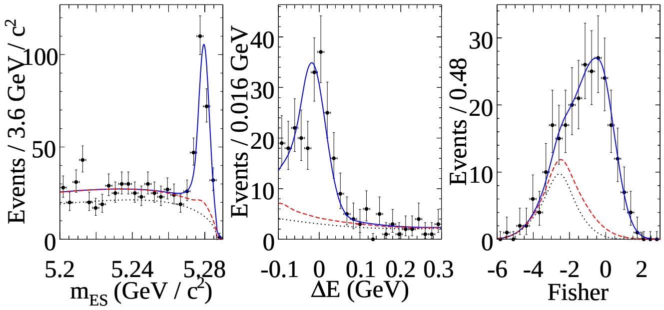

FIG. 1: Signal enhanced distribution (see text) of (left) $m_{\rm ES}$, (middle) ΔE, and (right) $\mathcal{F}$ for the data (points), sum of signal and backgrounds (solid line), sum of backgrounds (dashed line), and the continuum background (dotted line).

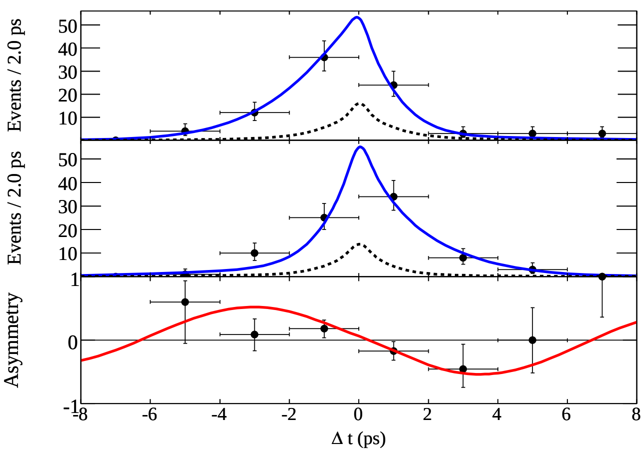

FIG. 2: The Δt distribution for a sample of signal enhanced events (see text) tagged as B^0 (top) and $\overline{B}^0$ (middle), where dotted lines are the sum of backgrounds and solid lines are the sum of signal and backgrounds. The time-dependent *CP* asymmetry (see text) is also shown (bottom), where the curve represents the measured asymmetry.

by-event beam spot position are found to be small. We determine the fit bias on signal parameters from ensembles of generated experiments using signal MC simulated data, which is generated using the GEANT4-based [18] *BABAR* MC simulation, embedded into MC samples of background simulated from the PDFs as described in Ref. [17]. We apply corrections to account for the observed fit bias on the signal yield, S, and C of -2.7 events, -0.034, and -0.022, respectively. The uncertainty coming from this correction is taken as half of the correction added in quadrature with the error on the correction. Most, but not all, of the inclusive charmonium final states that dominate the inclusive B background are precisely known from previous measurements. Their yields are fixed in the fit. As a cross check, yields for the B backgrounds are allowed to vary one at a time. The

TABLE I: Contributions to the systematic errors on the signal yield, S, and C, where the signal yield errors are given as number of events. The total systematic uncertainty is the quadratic sum of the individual contributions listed. Additional systematic uncertainties that are applied only to the branching fraction are discussed in the text.

Contribution	Yield	S	C
PDF parameterization	$^{+0.5}_{-1.6}$	$^{+0.010}_{-0.012}$	$^{+0.002}_{-0.011}$
Boost and z-scale	±1.1	±0.001	±0.002
Beam spot position	...	±0.004	±0.002
Fit bias	$\pm$ 1.5	±0.021	±0.014
B background yields	±1.2	±0.029	±0.013
CP content of B background	±0.4	±0.002	±0.002
Tag side interference	...	±0.004	±0.014
Total	$^{+2.3}_{-2.7}$	±0.04	±0.03

sum in quadrature of deviations from the nominal result is taken as a systematic uncertainty. In order to evaluate the uncertainty coming from *CP* violation in the B background, where appropriate, we introduce non-zero S and C for each background in turn. The uncertainty due to *CP* violation in $B^0 \to J/\psi K^0_S$ is determined by varying S and C within current experimental limits [14, 19]. For B background events decaying into final states with charm, we allow for a 20% asymmetry, and we allow for 100% asymmetries in all other B backgrounds. We study the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ amplitude for some tag-side B decays [20]. Systematic uncertainties from the effect of mis-alignment of the vertex detector and the use of an effective lifetime for inclusive B and $J/\psi K^{*0}$ backgrounds are found to be negligible. There are additional systematic uncertainties that contribute only to the branching fraction. These come from uncertainties for π^0 meson reconstruction efficiency (3%), the $J/\psi \to \ell^+\ell^-$ branching fractions (1.4%), the number of B meson pairs (1.1%), and tracking efficiency (1.0%). We apply a correction for charged particle identification efficiency (-1.3 ± 0.7% for $J/\psi \to e^+e^-$, and -3.3 ± 1.0% for $J/\psi \to \mu^+\mu^-$ decays) based on the results of control sample studies using B decays with J/ψ mesons in the final state. The systematic error contribution from MC statistics is negligible.

We measure

$$\begin{aligned} \mathcal{B} &= (1.69 \pm 0.14({\rm stat}) \pm 0.07({\rm syst})) \times 10^{-5}, \\ S &= -1.23 \pm 0.21({\rm stat}) \pm 0.04({\rm syst}), \\ C &= -0.20 \pm 0.19({\rm stat}) \pm 0.03({\rm syst}), \end{aligned}$$

where the correlation between S and C is 19.7%. We determine the significance, including systematic uncertainties, of non-zero values of S and C using ensembles of MC simulated experiments as outlined in Ref. [21]. The significance of S or C being non-zero is 4.0σ, which constitutes evidence for CP violation in $B^0 \rightarrow J/\psi\pi^0$ decays. The numerical values of S and C are consistent with the SM expectations for a tree-dominated $b \rightarrow c\overline{c}d$ transition. All results presented here are consistent with previous measurements [9–11].

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