Measurement of the CP-Violation Parameter $\sin(2\beta)$ in $B_d^0/\overline{B}_d^0 \to J/\psi K_S^0$ Decays

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We present a measurement of the time-dependent asymmetry in the rate for $\overline{B}_d^0$ versus B_d^0 decays to $J/\psi K_S^0$. A nonzero asymmetry would be an indication of CP violation, and within the standard model this may be used to measure the CP-violation parameter $\sin(2\beta)$. A total of 198 ± 17 $B_d^0/\overline{B}_d^0$ decays were observed in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV by the CDF detector at the Fermilab Tevatron. B_d^0 and $\overline{B}_d^0$ are distinguished by a technique based on charge correlations from hadronization of the b quark. Our analysis results in $\sin(2\beta) = 1.8 \pm 1.1(\text{stat}) \pm 0.3(\text{syst})$. [S0031-9007(98)08036-3]

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The origin of charge-conjugation–parity (CP) nonconservation has been an outstanding question in physics since its unexpected discovery in $K_L^0 \to \pi^+\pi^-$ decays in 1964 [1]. A popular mechanism for explaining CP violation is through the relationship between the weak interaction and the mass eigenstates of quarks. This relationship is described in the standard model (SM) by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [2]. With the addition of the third generation of quarks, top and bottom, this matrix gains a physical complex phase capable of accommodating CP violation.

After more than three decades, CP violation has been observed in the K^0-$\overline{K}^0$ system alone. Searches for CP violation have recently been extended to inclusive B meson decays. However, the effects are expected to be small ($\sim 10^{-3}$) in the SM [3], and no measurement has had the precision to reveal an effect [4].

In the SM, a large time-dependent CP asymmetry is expected in the relative decay rates of B_d^0 and $\overline{B}_d^0$ to the CP eigenstate $J/\psi K_S^0$ [3]. The interference of direct decays ($B_d^0 \to J/\psi K_S^0$) vs those that have undergone mixing ($B_d^0 \to \overline{B}_d^0 \to J/\psi K_S^0$) gives rise to a decay asymmetry [5,6]

$$\mathcal{A}_{CP}(t) \equiv \frac{\overline{B}_d^0(t) - B_d^0(t)}{\overline{B}_d^0(t) + B_d^0(t)} = \sin(2\beta)\sin(\Delta m_d t)\,, \quad (1)$$

where $B_d^0(t)$ [$\overline{B}_d^0(t)$] is the number of decays to $J/\psi K_S^0$ at proper time t given that the produced meson (at $t = 0$) was a B_d^0 ($\overline{B}_d^0$). The CP-violating phase between the direct and mixed paths is described in Eq. (1) by the factor $\sin(2\beta)$, and the time-dependent flavor oscillation by the second factor, where Δm_d is the mass difference between the B_d^0 eigenstates. Within the SM, constraints on the CKM matrix imply $0.30 \leq \sin(2\beta) \leq 0.88$ at 95% C.L. (confidence level) [7]. Using a $J/\psi K_S^0$ sample, the OPAL Collaboration has recently reported $\sin(2\beta) = 3.2^{+1.8}_{-2.0} \pm 0.5$ [8].

Here we report on an analysis using $B_d^0/\overline{B}_d^0 \to J/\psi K_S^0$ decays extracted from a data sample with an integrated luminosity of 110 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV collected in 1992–1996 by the CDF detector at the Fermilab Tevatron collider. A description of the CDF detector may be found in Refs. [9,10].

The $B_d^0/\overline{B}_d^0 \to J/\psi K_S^0$ sample selection [11] closely parallels Ref. [12]. The decays of the J/ψ to $\mu^+\mu^-$ are reconstructed. Both muons must be measured by our silicon vertex detector [10], thereby providing a precise decay length measurement. K_S^0 candidates are sought by fitting pairs of oppositely charged tracks, assumed to be pions, to the $K_S^0 \to \pi^+\pi^-$ hypothesis. The J/ψ and K_S^0 daughter tracks are combined in a four particle fit assuming they arise from $B_d^0/\overline{B}_d^0 \to J/\psi K_S^0$: the $\mu^+\mu^-$ and $\pi^+\pi^-$ are constrained to their parents' world average masses and separate decay vertices, and the K_S^0 and B are constrained to point back to their points of origin. A B candidate is accepted if its transverse momentum with respect to the beam line $p_T(B)$ is greater than 4.5 GeV$/c$, and if the K_S^0 candidate has $p_T(K_S^0) > 0.7$ GeV$/c$ and a decay vertex significantly displaced from the J/ψ vertex. Fit quality criteria are also applied.

We define $M_N \equiv (M_{\rm FIT} - M_0)/\sigma_{\rm FIT}$, where $M_{\rm FIT}$ is the mass of the B candidate from the fit described above, $\sigma_{\rm FIT}$ is its uncertainty (typically ~ 9 MeV$/c^2$), and M_0 is the central value of the B_d^0 mass peak. The decay length of the B is used to calculate its proper decay length ct, which includes the sign from the scalar product of the transverse components of the vectors for the B decay vertex displacement from the $p\overline{p}$ interaction vertex and the B momentum. The normalized masses M_N for the accepted candidates with $ct > 0$ are shown in Fig. 1a, along with the results of the likelihood fit described later. The fit yields (for all ct) 198 ± 17 $B_d^0/\overline{B}_d^0$ mesons, with a Gaussian rms of 1.39 ± 0.11 (similar to other $B \to J/\psi K$ reconstructions [12]).

Measuring $\mathcal{A}_{CP}(t)$ is predicated upon knowing whether the production "flavor" of the meson was B_d^0 or $\overline{B}_d^0$; such identification is referred to as flavor "tagging." We use a same-side tagging (SST) method which relies upon the correlation between the B flavor and the charge of a nearby particle. Such a correlation can arise from the fragmentation processes which form a B meson from a $\overline{b}$ quark, as well as from the pion from the decay of B^{**} mesons [13]. In both cases, a B_d^0 is preferentially associated with a positive particle, and a $\overline{B}_d^0$ with a negative one. The effectiveness of this method has been demonstrated by tagging $B \to \nu \ell D^{(*)}$ decays and observing the time dependence of the B_d^0-$\overline{B}_d^0$ oscillation and measuring Δm_d. We have also measured the amplitude of the oscillation (i.e., the strength of the correlation) in a lower-statistics $B_d^0 \to J/\psi K^{*0}$ sample and found it to be consistent with the $\nu \ell D^{(*)}$ data [12,14].

Our SST method, following Ref. [14], selects a single charged particle as a flavor tag from those within an η-ϕ cone of half-angle 0.7 around the B direction, where $\eta \equiv -\ln[\tan(\theta/2)]$ is the pseudorapidity, θ is the polar angle relative to the proton beam direction, and ϕ is the

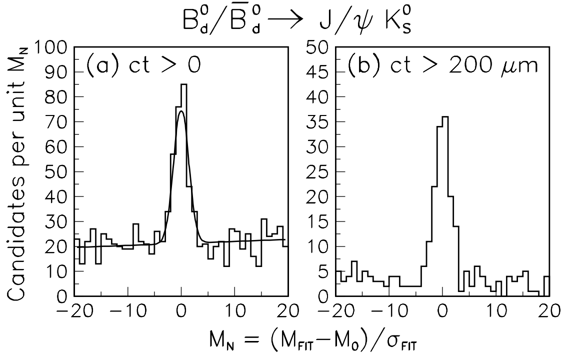

FIG. 1. The normalized mass distributions of the $J/\psi K_S^0$ candidates with $ct > 0$ and 200 μm. The curve is the Gaussian signal plus linear background from the likelihood fit (see text).

azimuthal angle around the beam line. The tag must have $p_T > 400$ MeV/c and come from the $p\overline{p}$ interaction vertex (i.e., have a transverse impact parameter within 3 standard deviations of the interaction vertex). If there is more than one candidate, the one with the smallest $p_T^{\rm rel}$ is selected as *the* flavor tag, where the $p_T^{\rm rel}$ of a particle is the component of its momentum transverse to the momentum of the combined B + particle system.

We apply the SST method to the $J/\psi K_S^0$ sample. The tagging efficiency is ~65%. The breakdown of tags is given in Table I in proper time bins. We call $|M_N| < 3$ the "signal region" and $3 < |M_N| < 20$ the "sidebands." Since negative (positive) tags are associated with $\overline{B}_d^0$'s (B_d^0's), we form the asymmetry

$$\mathcal{A}(ct) \equiv \frac{N^-(ct) - N^+(ct)}{N^-(ct) + N^+(ct)} \tag{2}$$

analogous to Eq. (1), where $N^{\pm}(ct)$ are the numbers of positive and negative tags in a given ct bin. The signal events generally have a positive asymmetry (i.e., favoring negative tags) at large ct. The sidebands show a consistent negative asymmetry (i.e., favoring positive tags), but this has a small effect in the sideband-subtracted asymmetry at larger ct, where the signal purity is high (see Fig. 1b).

The sideband-subtracted asymmetries of Table I are displayed in Fig. 2 along with a χ^2 fit (dashed curve) to $\mathcal{A}_0 \sin(\Delta m_d t)$, where Δm_d is fixed to 0.474 ps^{-1} [15] (χ^2 per degree of freedom is 2.38/5). The amplitude, $\mathcal{A}_0 = 0.36 \pm 0.19$, measures $\sin(2\beta)$ attenuated by a "dilution factor" $\mathcal{D}_0 \equiv 2\mathcal{P}_0 - 1$, where $\mathcal{P}_0$ is the probability that the tag correctly identifies the B_d^0 flavor. The determination of $\mathcal{A}_0$ is dominated by the asymmetries at larger ct's due to the $\sin(\Delta m_d t)$ shape; this is also where the background is very low.

We refine the fit using an unbinned maximum likelihood fit based on Ref. [12]. This fit makes optimal use of the low statistics by fitting signal and background distributions in M_N and ct, including sideband and $ct < 0$ events which help constrain the background. The likelihood fit also incorporates resolution effects and corrections for systematic biases, such as the inherent charge asymmetry favoring positive tracks resulting from the wire plane orientation in the main drift chamber.

TABLE I. Tags for the $J/\psi K_S^0$ candidates in proper decay length (ct) bins. The signal region is $|M_N| < 3$, and the sidebands are $3 < |M_N| < 20$. The "+," "−," and "0" headings are for positive, negative, and untagged events, respectively. The last column is the sideband-subtracted tagging asymmetry [Eq. (2)]. The asymmetry for the background-dominated first row is not quoted because there is not a tagged, sideband-subtracted excess.

	Signal			Sidebands			
ct (μm)	−	+	0	−	+	0	Asymmetry (%)
−200–0	42	21	43	167	193	174	⋯
0–100	53	48	49	156	175	205	20 ± 25
100–200	14	14	15	26	34	24	8 ± 32
200–400	12	18	19	17	22	10	−22 ± 24
400–800	26	13	22	11	18	11	42 ± 18
800–1400	6	4	9	6	6	2	25 ± 40
1400–2000	3	1	1	0	0	2	50 ± 43

We measure the inherent charge asymmetry of the tagging in a large inclusive (unflavored) J/ψ sample with displaced decay vertices (>90% b hadrons) and parametrize its dependence on track p_T and event occupancy. The occupancy dependence is weak. At 400 MeV/c, the SST p_T threshold, the asymmetry is (5.6 ± 1.1)%, falling as p_T^{-4} to (0.14 ± 0.86)% at high p_T [the average tag asymmetry in the J/ψ sample is (1.6 ± 0.7)%], all favoring positive tags. This correction is applied to the signal in the likelihood fit; the charge asymmetry of the $J/\psi K_S^0$ background is measured independently by the fit itself.

The solid curve in Fig. 2 is the result of the likelihood fit, which gives $\mathcal{D}_0 \sin(2\beta) = 0.31 \pm 0.18$. As expected, the two types of fits give similar results, indicating that our result is dominated by the sample size and that the corrections and improvements of the likelihood fit introduce no dramatic effects. Also shown in the Fig. 2 inset is the relative log-likelihood as a function of $\mathcal{D}_0 \sin(2\beta)$; the shape is parabolic, indicating Gaussian errors. As a test of the goodness of fit, we compared the fitted likelihood of the data to results obtained from Monte Carlo pseudoexperiments and found 45% of them were more improbable than the data.

As noted above, the sidebands favor positive tags. The maximized likelihood ascribes an asymmetry of (16.7 ± 8.2)% favoring positive tags, or an ~2σ excess, to the long-lived backgrounds (e.g., $B \to J/\psi X$ with an

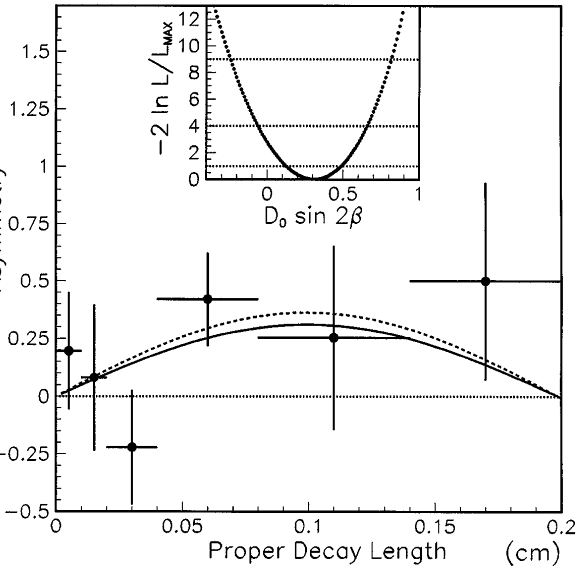

FIG. 2. The sideband-subtracted flavor asymmetry [as defined by Eq. (1)] as a function of the reconstructed $J/\psi K_S^0$ proper decay length (points). The dashed curve is the result of a simple χ^2 fit to $\mathcal{A}_0 \sin(\Delta m_d t)$. The solid curve is the likelihood fit result, and the inset shows a scan through the log-likelihood function as $\mathcal{D}_0 \sin(2\beta)$ is varied about the best fit value.

unassociated K_S^0). Prompt background (consistent with ct resolution) has an asymmetry of (0.6 ± 4.5)% favoring negative tags.

Systematic effects from B backgrounds have been considered. For instance, the decay $B_d^0 \to J/\psi K^{*0}$, $K^{*0} \to K_S^0 \pi^0$, where we do not reconstruct the π^0, has a negligible effect on the result. Background asymmetries were also studied in $J/\psi K^+$ and $J/\psi K^{*0}$ modes [12]. No systematic pattern emerged. Since no other biases have been found aside from the above small effects, we attribute the background asymmetry largely to statistical fluctuations. Again, the effect of these asymmetries is small as the total background fraction is small at large ct (see Fig. 1b) where $\sin(\Delta m_d t)$ is large.

We determine the systematic uncertainty on $\mathcal{D}_0 \sin(2\beta)$ by shifting the central value of each fixed input parameter to the fit by $\pm 1\sigma$ and refitting to find the shift in $\mathcal{D}_0 \sin(2\beta)$. Varying the B_d^0 lifetime (468 ± 18 μm [15]) shifts the central value by ±0.001. The parametrization of the intrinsic charge asymmetry is also varied, yielding a $^{+0.016}_{-0.019}$ uncertainty. The largest systematic uncertainty is due to $\Delta m_d = 0.474 \pm 0.031$ ps^{-1} [15], which gives a $^{+0.029}_{-0.025}$ shift. These systematic uncertainties are added in quadrature, giving $\mathcal{D}_0 \sin(2\beta) = 0.31 \pm 0.18 \pm 0.03$.

To obtain $\sin(2\beta)$, we use dilution measurements from other B samples. Our best single $\mathcal{D}_0$ measurement, from a large $B \to \ell D^{(*)} X$ sample, is $0.181^{+0.036}_{-0.032}$ [12,14]. Because of differing lepton p_T trigger thresholds, the average p_T of the semileptonic B's is ~21 GeV/c, but it is only 12 GeV/c in the $J/\psi K_S^0$ data. We correct for this difference by using a version of the PYTHIA event generator [16] tuned to CDF data [12,17]. We supplement the above measurement of $\mathcal{D}_0$ with the dilution $\mathcal{D}_+$ measured from B^+'s in the same $\ell D^{(*)}$ sample, as well as measurements from $B \to J/\psi K^+$ and $J/\psi K^{*0}$. The simulation also accounts for the systematic difference between B_d^0 and B^+ dilutions. The $\mathcal{D}_0$ appropriate for our $J/\psi K_S^0$ sample is then 0.166 ± 0.018 ± 0.013, a small shift from 0.181. The first error is due to the uncertainty in the dilution measurements, and the second is due to the Monte Carlo extrapolation. The latter is determined by surveying a range of simulation parameters [11,12].

Using this $\mathcal{D}_0$, we find that $\sin(2\beta) = 1.8 \pm 1.1 \pm 0.3$. The central value is unphysical since the amplitude of the measured asymmetry is larger than $\mathcal{D}_0$. If one wishes to frame this result in terms of confidence intervals, various alternatives are available [15,18]. We follow the frequentist construction of Ref. [18], which gives proper confidence intervals even for measurements in the unphysical region. Our measurement thereby corresponds to excluding $\sin(2\beta) < -0.20$ at 95% C.L. We also calculate that, if the true value of $\sin(2\beta)$ were 1, the median expectation of an exclusion for an analysis like ours would be $\sin(2\beta) < -0.89$ at 95% C.L. This is a measure of experimental sensitivity [18]; our limit is higher, reflecting the excursion into the unphysical region.

It is interesting to note that, as long as $\mathcal{D}_0 \neq 0$, the exclusion of $\sin(2\beta) = 0$ is *independent* of the value of $\mathcal{D}_0$. Given $\mathcal{D}_0 > 0$, the same prescription as above yields a dilution-independent exclusion of $\sin(2\beta) < 0$ at 90% C.L.

We have explored the robustness of our result by varying selection and tagging criteria. None had a significant effect on the asymmetry, with the exception of the tagging p_T threshold. In principle, any choice of the threshold would give an unbiased estimator of $\mathcal{D}_0 \sin(2\beta)$. The 400 MeV/$c$ threshold, however, was our *a priori* choice as a compromise between the tracking asymmetry at lower p_T and the reduced tagging efficiency at higher p_T.

When varying the p_T threshold we found that $\mathcal{D}_0 \sin(2\beta)$ drops rather sharply in going from 0.5 to 0.6 GeV/c, and then gradually rises. The probability of observing such a large change in an ~100 MeV/c step is estimated to be ~5%. The smallest value of $\mathcal{D}_0 \sin(2\beta)$ is -0.21 ± 0.21 (stat. error only) for a 0.7 GeV/c threshold. This variation cannot be attributed to the dependence of $\mathcal{D}_0$ on the p_T threshold: both the charged and neutral dilution measurements vary slowly, in good agreement with the PYTHIA calculations [12]. Moreover, no systematic effects have been found which are able to account for such a variation.

As we can identify no mechanism to give the particular behavior seen, we characterize the variation of $\mathcal{D}_0 \sin(2\beta)$ with the p_T threshold by calculating the probability that the variation in the data agrees with the slow variation in the simulation. To this end, we employ the χ^2 procedure used in Ref. [12] to study the dilution variation in a $B^+ \to J/\psi K^+$ sample. We compare the data with Monte Carlo pseudoexperiments of similar size and find that the probability of obtaining a higher χ^2 (*worse* agreement) than the data is 42%, considering only statistical fluctuations [11]. Thus, the observed variation of $\mathcal{D}_0 \sin(2\beta)$ with the SST p_T threshold is consistent with statistical fluctuations expected for a sample of this size.

In summary, we have applied a same-side flavor tagging method to a sample of $B_d^0/\overline{B}_d^0 \to J/\psi K_S^0$ decays and measured $\sin(2\beta) = 1.8 \pm 1.1 \pm 0.3$. Although the sensitivity of the result on the tagging p_T threshold complicates the interpretation, our result favors current standard model expectations of a positive value of $\sin(2\beta)$.

This result establishes the feasibility of measuring CP asymmetries in B meson decays at a hadron collider. Operation of the Main Injector in the next Tevatron Collider run should provide more than an order of magnitude increase in luminosity. Detector upgrades will further enlarge our B samples. If current expectations are correct, these large samples should be sufficient to observe and study CP violation in $J/\psi K_S^0$, and possibly in other modes as well [19].

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