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Measurement of the *CP* Asymmetry Amplitude sin2*β*

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We present results on time-dependent CP asymmetries in neutral B decays to several CP eigenstates. The measurements use a data sample of about 88 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected between 1999 and 2002 with the *BABAR* detector at the PEP-II asymmetric-energy B Factory at SLAC. We study events in which one neutral B meson is fully reconstructed in a final state containing a charmonium meson and the other B meson is determined to be either a B^0 or $\overline{B}^0$ from its decay products. The amplitude of the CP asymmetry, which in the Standard Model is proportional to sin2β, is derived from the decay-time distributions in such events. We measure $\sin 2\beta = 0.741 \pm 0.067$ (stat) ± 0.034 (syst) and $|\lambda| = 0.948 \pm 0.051$ (stat) ± 0.030 (syst). The magnitude of λ is consistent with unity, in agreement with the Standard Model expectation of no direct CP violation in these modes.

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The Standard Model of electroweak interactions describes CP violation in weak interactions as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, measurements of *CP* asymmetries in the proper-time distribution of neutral B decays to charmonium final states provide a direct measurement of sin2β [2], where $\beta \equiv \arg\left[-V_{\rm cd}V_{\rm cb}^{*}/V_{\rm td}V_{\rm tb}^{*}\right]$.

Observations of *CP* violation in B^0 decays were reported last year by the *BABAR* [3] and Belle [4] collaborations. The PEP-II collider has since delivered an additional 63 fb^{-1}, thereby approximately tripling the data sample near the Υ(4S) resonance. In this Letter we report a more precise measurement of sin2β using the full sample of about 88 million $B\overline{B}$ decays. The *BABAR* detector and the measurement technique are described in detail in Refs. [5] and [6], respectively. Changes in the analysis with respect to the published result [3] include processing of all data with a uniform event reconstruction, a new flavor-tagging algorithm, and the addition of the decay mode $B^0 \to \eta_c K^0_S$.

We reconstruct a sample of neutral B mesons (B_{CP}) decaying to the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, $J/\psi K^{*0}(K^{*0}\to K^0_S\pi^0)$, and $J/\psi K^0_L$. The J/ψ and $\psi(2S)$ mesons are reconstructed through their decays to e^+e^- and $\mu^+\mu^-$; the $\psi(2S)$ is also reconstructed through its decay to $J/\psi\pi^+\pi^-$. We reconstruct χ_{c1} mesons in the decay mode $J/\psi\gamma$ and η_c mesons in the $K^0_S K^+\pi^-$ and $K^+K^-\pi^0$ final states [7]. The K^0_S is reconstructed in its decay to $\pi^+\pi^-$ (and to $\pi^0\pi^0$ for the $J/\psi K^0_S$ mode). We examine each event in the B_{CP} sample for evidence that the recoiling B meson decayed as a B^0 or $\overline{B}{}^0$ (flavor tag).

The proper-time distribution of B meson decays to a *CP* eigenstate with a B^0 or $\overline{B}{}^0$ tag can be expressed in terms of a complex parameter λ that depends on both the B^0-$\overline{B}{}^0$ oscillation amplitude and the amplitudes describing $\overline{B}{}^0$ and B^0 decays to this final state [8]. The decay rate $\mathrm{f}_+(\mathrm{f}_-)$ when the tagging meson is a $B^0(\overline{B}{}^0)$ is given by

$$\mathrm{f}_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 \pm \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}\sin(\Delta m_d\Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2}\cos(\Delta m_d\Delta t)\right], \quad (1)$$

where $\Delta t = t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay times of the reconstructed B meson ($B_{\rm rec}$) and the tagging B meson ($B_{\rm tag}$), τ_{B^0} is the B^0 lifetime, and Δm_d is the B^0-$\overline{B}{}^0$ oscillation frequency. The sine term in Eq. 1 is due to the interference between direct decay and decay after flavor change, and the cosine term is due to the interference between two or more decay amplitudes with different weak and strong phases. *CP* violation can be observed as a difference between the Δt distributions of B^0- and $\overline{B}{}^0$-tagged events or as an asymmetry with respect to $\Delta t = 0$ for either flavor tag.

In the Standard Model, $\lambda = \eta_f e^{-2i\beta}$ for charmonium-containing $b \to c\overline{c}s$ decays, where η_f is the *CP* eigenvalue of the final state f. Thus, the time-dependent *CP* asymmetry is

$$A_{CP}(\Delta t) \equiv \frac{\mathrm{f}_+(\Delta t) - \mathrm{f}_-(\Delta t)}{\mathrm{f}_+(\Delta t) + \mathrm{f}_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_d\,\Delta t), \quad (2)$$

with $\eta_f = -1$ for $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$, and $+1$ for $J/\psi K^0_L$. Due to the presence of even (L=0, 2) and odd (L=1) orbital angular momenta in the $B \to J/\psi K^{*0}$ final state, there can be *CP*-even and *CP*-odd contributions to the decay rate. When the angular information in the decay is ignored, the measured *CP* asymmetry in $J/\psi K^{*0}$ is reduced by a factor $1-2R_\perp$, where $R_\perp$ is the fraction of the L=1 component. We have measured $R_\perp = (16.0\pm3.5)\%$ [9], which gives $\eta_f = 0.65\pm0.07$ after acceptance corrections in the $J/\psi K^{*0}$ mode.

The event selection, lepton and $K^\pm$ identification, and J/ψ and $\psi(2S)$ reconstruction used in this analysis are similar to those described in Ref. [6], as are the selection criteria for the channels $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $J/\psi K^{*0}$, and $J/\psi K^0_L$. The $B^0 \to \eta_c K^0_S$ sample selection is described in Ref. [10]. In brief, the $K^\pm$ candidates must satisfy kaon identification criteria and the $K^0_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$ candidates are required to have reconstructed masses within 12.5 and 15 MeV/c^2, respectively, of their nominal masses [11]. The η_c candidates (with $2.90 < M_{KK\pi} < 3.15\,\mathrm{GeV}/c^2$) are combined with $K^0_S \to \pi^+\pi^-$ candidates reconstructed within 10 MeV/c^2 of the K^0_S nominal mass to form a B^0 candidate. This sample includes a contribution of $(15\pm2)\%$ from hadronic J/ψ decays to the $KK\pi$ final states.

We select candidates in the $B^0 \to J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $J/\psi K^{*0}$ sample by requiring that the difference ΔE between their energy and the beam energy in the center-of-mass frame be less than three standard deviations from zero. The ΔE resolution is about 10 MeV, except for the mode with $K^0_S \to \pi^0\pi^0$ (33 MeV) and with K^{*0} (20 MeV). The $B^0 \to \eta_c K^0_S$ candidates are required to have $|\Delta E|$ less than 40 (70) MeV for the $K^0_S K^+\pi^-$ ($K^+K^-\pi^0$) modes. For all modes except $J/\psi K^0_L$, the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E^{\rm cm}_{\rm beam})^2 - (p^{\rm cm}_B)^2}$ must be greater than 5.2 GeV/c^2. To determine numbers of events and purities, a signal region $5.270\ (5.273) < m_{\rm ES} < 5.290\ (5.288)\,\mathrm{GeV}/c^2$ is used for modes containing K^0_S (K^{*0}). In the $J/\psi K^0_L$ mode, the ΔE resolution is 3.5 MeV (after B mass constraint) and the signal region is defined by $|\Delta E| < 10\,\mathrm{MeV}$.

A measurement of A_{CP} requires a determination of the experimental Δt resolution and the fraction w of events in which the tag assignment is incorrect. This mistag fraction reduces the observed *CP* asymmetry by a factor $1-2w$. Mistag fractions and Δt resolution functions are determined from a sample of neutral B mesons that decay to flavor eigenstates ($B_{\rm flav}$) consisting of the channels $D^{(*)-}h^+(h^+ = \pi^+, \rho^+$, and $a_1^+)$ and

$J/\psi\, K^{*0}(K^{*0} \rightarrow K^+\pi^-)$. Validation studies are performed with a control sample of B^+ mesons decaying to the final states $J/\psi\, K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, $\eta_c K^+$, and $\overline{D}^{(*)0}\pi^+$.

We use multivariate algorithms to identify signatures of B decays that determine the flavor of $B_{\rm tag}$. Primary leptons from semileptonic B decays are selected from identified electrons and muons as well as isolated energetic tracks. We use the charges of identified kaon candidates to define a kaon tag. Soft pions from D^{*+} decays are selected on the basis of their momentum and direction with respect to the thrust axis of $B_{\rm tag}$. A neural network, which combines the outputs of these physics-based algorithms, takes into account correlations between different sources of flavor information and provides an estimate of the mistag probability for each event.

By using the outputs of the physics-based algorithms and the estimated mistag probability, each event is assigned to one of four hierarchical, mutually exclusive tagging categories. The `Lepton` category contains events with an identified lepton, and a supporting kaon tag if present. Events with a kaon candidate and soft pion with opposite charge and similar flight direction are assigned to the `Kaon I` category. Events with only a kaon tag are assigned to the `Kaon I` or `Kaon II` category depending on the estimated mistag probability. The `Kaon II` category also contains the remaining events with a soft pion. All other events are assigned to the `Inclusive` category or excluded from further analysis based on the estimated mistag probability. The tagging efficiencies ε_i for the four tagging categories are measured from data and summarized in Table I. The figure of merit for tagging is the effective tagging efficiency $Q \equiv \sum_i \varepsilon_i(1-2w_i)^2$. This algorithm improves Q by about 7% (relative) over the algorithm used in Ref. [6].

The time interval Δt between the two B decays is calculated from the measured separation Δz between the decay vertices of $B_{\rm rec}$ and $B_{\rm tag}$ along the collision (z) axis [6]. We determine the z position of the $B_{\rm rec}$ vertex from its charged tracks. The $B_{\rm tag}$ decay vertex is determined by fitting tracks not belonging to the $B_{\rm rec}$ candidate to a common vertex, employing constraints from the beam spot location and the $B_{\rm rec}$ momentum [6]. We accept events with a Δt uncertainty of less than 2.5 ps and $|\Delta t| < 20$ ps. The fraction of events satisfying these requirements is 95%. The r.m.s. Δt resolution for 99.7% of these events is 1.1 ps.

The signal region contains 2641 events which satisfy the tagging and vertexing requirements. In Table II we list the number of events and the signal purity for the tagged B_{CP} candidates. The purities are determined from fits to the $m_{\rm ES}$ (all K^0_S modes) or ΔE (K^0_L mode) distributions in data, or from Monte Carlo simulation (K^{*0} mode). Figure 1 shows the $m_{\rm ES}$ distribution for modes containing a K^0_S or K^{*0} and ΔE distribution for the $J/\psi\, K^0_L$ candidates. For all modes except $\eta_c K^0_S$ and $J/\psi\, K^0_L$, we use simulated events to estimate the fractions of events in the Gaussian component of the $m_{\rm ES}$ fits due to cross-feed from other decay modes. For the $\eta_c K^0_S$ mode the cross-feed fraction is determined from a fit to the $M_{KK\pi}$ and $m_{\rm ES}$ distributions. These fractions range from $(0.3 \pm 0.1)\%$ for $J/\psi\, K^0_S$ ($K^0_S \rightarrow \pi^+\pi^-$) to $(13.1 \pm 5.9)\%$ for $\eta_c K^0_S$. For the $J/\psi\, K^0_L$ and $J/\psi\, K^{*0}$ decay modes, the composition, effective η_f, and ΔE distribution ($J/\psi\, K^0_L$ only) of the individual background sources are determined either from simulation (for $B \rightarrow J/\psi\, X$) or from the $m_{\ell^+\ell^-}$ sidebands in data (for fake $J/\psi \rightarrow \ell^+\ell^-$).

TABLE I: Efficiencies ϵ_i, average mistag fractions w_i, mistag fraction differences $\Delta w_i = w_i(B^0) - w_i(\overline{B}^0)$, and Q extracted for each tagging category i from the $B_{\rm flav}$ and B_{CP} samples.

Category	ε (%)	w (%)	Δw (%)	Q (%)
`Lepton`	9.1 ± 0.2	3.3 ± 0.6	-1.5 ± 1.1	7.9 ± 0.3
`Kaon I`	16.7 ± 0.2	10.0 ± 0.7	-1.3 ± 1.1	10.7 ± 0.4
`Kaon II`	19.8 ± 0.3	20.9 ± 0.8	-4.4 ± 1.2	6.7 ± 0.4
`Inclusive`	20.0 ± 0.3	31.5 ± 0.9	-2.4 ± 1.3	2.7 ± 0.3
All	65.6 ± 0.5			28.1 ± 0.7

We determine sin2β with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the tagged B_{CP} and $B_{\rm flav}$ samples. In this fit the Δt distributions of the B_{CP} sample are described by Eq. 1 with $|\lambda| = 1$. The Δt distributions of the $B_{\rm flav}$ sample evolve according to the known frequency for flavor oscillation in

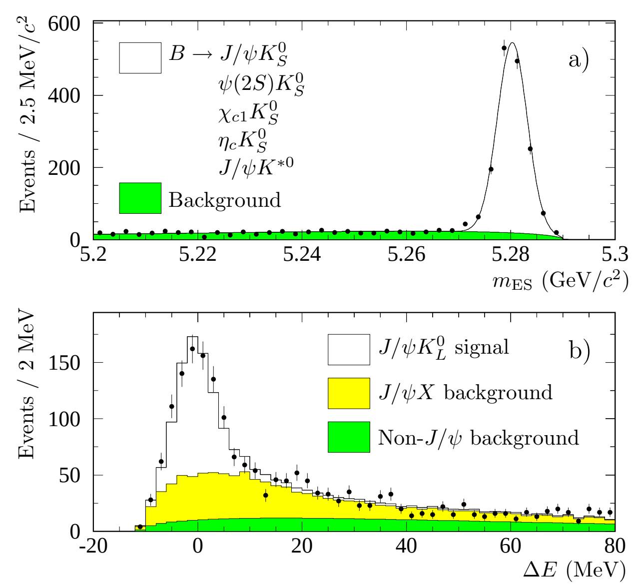

FIG. 1: Distributions for B_{CP} candidates satisfying the tagging and vertexing requirements: a) $m_{\rm ES}$ for the final states $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$, and $J/\psi K^{*0}(K^{*0} \rightarrow K^0_S\pi^0)$, and b) ΔE for the final state $J/\psi\, K^0_L$.

TABLE II: Number of events $N_{\rm tag}$ in the signal region after tagging and vertexing requirements, signal purity P, and results of fitting for CP asymmetries in the B_{CP} sample and in various subsamples, as well as in the $B_{\rm flav}$ and charged B control samples. Errors are statistical only.

Sample	$N_{\rm tag}$	$P(\%)$	sin2β
$J/\psi K^0_S$,$\psi(2S)K^0_S$,$\chi_{c1}K^0_S$,$\eta_c K^0_S$	1506	94	0.76 ± 0.07
$J/\psi K^0_L$ ($\eta_f = +1$)	988	55	0.72 ± 0.16
$J/\psi K^{*0}(K^{*0} \to K^0_S\pi^0)$	147	81	0.22 ± 0.52
Full CP sample	2641	78	0.74 ± 0.07
$J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ only ($\eta_f = -1$)			
$J/\psi K^0_S$ ($K^0_S \to \pi^+\pi^-$)	974	97	0.82 ± 0.08
$J/\psi K^0_S$ ($K^0_S \to \pi^0\pi^0$)	170	89	0.39 ± 0.24
$\psi(2S)K^0_S$ ($K^0_S \to \pi^+\pi^-$)	150	97	0.69 ± 0.24
$\chi_{c1}K^0_S$	80	95	1.01 ± 0.40
$\eta_c K^0_S$	132	73	0.59 ± 0.32
`Lepton` category	220	98	0.79 ± 0.11
`Kaon I` category	400	93	0.78 ± 0.12
`Kaon II` category	444	93	0.73 ± 0.17
`Inclusive` category	442	92	0.45 ± 0.28
B^0 tags	740	94	0.76 ± 0.10
$\overline{B}^0$ tags	766	93	0.75 ± 0.10
$B_{\rm flav}$ sample	25375	85	0.02 ± 0.02
B^+ sample	22160	89	0.02 ± 0.02

B^0 mesons. The observed amplitudes for the CP asymmetry in the B_{CP} sample and for flavor oscillation in the $B_{\rm flav}$ sample are reduced by the same factor $1-2w$ due to flavor mistags. Events are assigned signal and background probabilities based on the $m_{\rm ES}$ (all modes except $J/\psi K^{*0}$ and $J/\psi K^0_L$) or ΔE ($J/\psi K^0_L$) distributions. The Δt distributions for the signal are convolved with a common resolution function, modeled by the sum of three Gaussians [6]. Backgrounds are incorporated with an empirical description of their Δt spectrum, containing prompt and non-prompt components convolved with a resolution function [6] distinct from that of the signal.

There are 34 free parameters in the fit: sin2β (1), the average mistag fractions w and the differences Δw between B^0 and $\overline{B}^0$ mistag fractions for each tagging category (8), parameters for the signal Δt resolution (8), and parameters for background time dependence (6), Δt resolution (3), and mistag fractions (8). We fix $\tau_{B^0} = 1.542\,{\rm ps}$ and $\Delta m_d = 0.489\,{\rm ps}^{-1}$ [11]. The determination of the mistag fractions and Δt resolution function parameters for the signal is dominated by the high-statistics $B_{\rm flav}$ sample. The measured mistag fractions are listed in Table I. Background parameters are determined from events with $m_{\rm ES} < 5.27\,{\rm GeV}/c^2$ (except $J/\psi K^0_L$ and $J/\psi K^{*0}$). The largest correlation between sin2β and any linear combination of the other free parameters is 0.13. We observe a bias of 0.014 ± 0.005 in the fitted value of sin2β in simulated events. Part of this bias (0.004) is due to a correlation between the mistag fractions and the Δt resolution not explicitly incorporated in the fit. Therefore we subtract 0.014 from the fitted value of sin2β in data and include 0.010 in the systematic error.

The fit to the B_{CP} and $B_{\rm flav}$ samples yields

$$\sin 2\beta = 0.741 \pm 0.067\ ({\rm stat}) \pm 0.034\ ({\rm syst}).$$

Figure 2 shows the Δt distributions and asymmetries in yields between B^0 tags and $\overline{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of Δt, overlaid with the projection of the likelihood fit result.

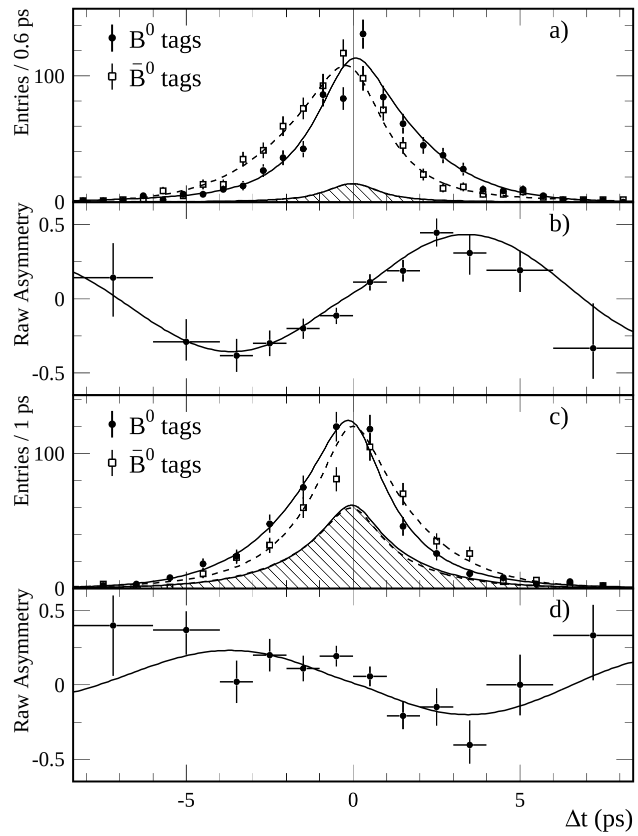

FIG. 2: a) Number of $\eta_f = -1$ candidates ($J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, and $\eta_c K^0_S$) in the signal region with a B^0 tag N_{B^0} and with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$ as functions of Δt. The solid (dashed) curves represent the fit projection in Δt for B^0 ($\overline{B}^0$) tags. The shaded regions represent the background contributions. Figures c) and d) contain the corresponding information for the $\eta_f = +1$ mode $J/\psi K^0_L$.

The dominant sources of systematic error are the uncertainties in the level, composition, and CP asymmetry of the background in the selected CP events (0.023), the assumed parameterization of the Δt resolution function (0.017), due in part to residual uncertainties in the internal alignment of the vertex detector, and possible differences between the $B_{\rm flav}$ and B_{CP} mistag fractions (0.012). The total systematic error is 0.034. Most systematic errors are determined with data and will continue to decrease with additional statistics.

The large B_{CP} sample allows a number of consistency checks, including separation of the data by decay mode, tagging category, and $B_{\rm tag}$ flavor. The results of fits to these $\eta_f = -1$ subsamples are shown in Table II and found to be statistically consistent. The results of fits to the control samples of non-*CP* decay modes indicate no statistically significant asymmetry.

We also measure the parameter $|\lambda|$ in Eq. 1 from a fit to the $\eta_f = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds. This parameter is sensitive to the difference in the number of B^0- and $\overline{B}^0$-tagged events. In order to account for differences in reconstruction and tagging efficiencies for B^0 and $\overline{B}^0$ mesons, we incorporate five additional free parameters in this fit. We obtain $|\lambda| = 0.948 \pm 0.051$ (stat) $\pm$ 0.030 (syst). The coefficient of the $\sin(\Delta m_d \Delta t)$ term in Eq. 1 is measured to be 0.759 ± 0.074 (stat). The dominant contribution to the systematic error for $|\lambda|$, conservatively estimated to be 0.025, is due to interference between the suppressed $\bar{b} \rightarrow \bar{u}c\bar{d}$ amplitude with the favored $b \rightarrow c\bar{u}d$ amplitude for some tag-side B decays. The other sources of systematic error for $|\lambda|$ are the same as in the $\sin 2\beta$ measurement.

This measurement of $\sin 2\beta$ supersedes our previous result [3] and improves upon the precision of each of the previous measurements [3, 4] by a factor of two. While the measured value is consistent with the range implied by the measurements and theoretical estimates of the magnitudes of CKM matrix elements in the context of the Standard Model, it provides a precise and model-independent constraint on the position of the apex of the Unitarity Triangle [12].

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