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Observation of CP Violation in the B^0 Meson System

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We present an updated measurement of time-dependent CP-violating asymmetries in neutral B decays with the *BABAR* detector at the PEP-II asymmetric B Factory at SLAC. This result uses an additional sample of $\Upsilon(4S)$ decays collected in 2001, bringing the data available to 32×10^6 $B\overline{B}$ pairs. We select events in which one neutral B meson is fully reconstructed in a final state containing charmonium and the flavor of the other neutral B meson is determined from its decay products. The amplitude of the CP-violating asymmetry, which in the standard model is proportional to $\sin 2\beta$, is derived from the decay time distributions in such events. The result $\sin 2\beta = 0.59 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{syst})$ establishes CP

violation in the B^0 meson system. We also determine $|\lambda| = 0.93 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$, consistent with no direct CP violation.

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CP violation has been a central concern of particle physics since its discovery in 1964 in the decays of K_L^0 mesons [1]. To date, this phenomenon has not been observed in any other system. An elegant explanation of this effect was proposed by Kobayashi and Maskawa, as a CP-violating phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2]. In this picture, measurements of CP-violating asymmetries in the time distributions of B^0 decays to charmonium final states provide a direct test of the standard model of electroweak interactions, free from strong interaction corrections [3].

Measurements of the CP-violating asymmetry parameter $\sin 2\beta$ have recently been reported by the *BABAR* [4] and Belle [5] Collaborations, from data taken in 1999–2000 at the PEP-II and KEKB asymmetric-energy e^+e^- colliders, respectively, with better precision than previous experiments [6]. In this Letter we report a new measurement of $\sin 2\beta$, enhanced by 9×10^6 $B\overline{B}$ pairs collected in 2001, additional decay modes, and improvements in data reconstruction and analysis. The *BABAR* detector and the experimental method are described in Refs. [4,7], so the discussion here is limited to items and issues pertinent to the current analysis.

The complete data set (32×10^6 $B\overline{B}$ pairs) has been used to fully reconstruct a sample B_{CP} of neutral B mesons decaying to the $J/\psi K_S^0$, $\psi(2S)K_S^0$, $J/\psi K_L^0$, $\chi_{c1}K_S^0$, and $J/\psi K^{*0}$ ($K^{*0} \to K_S^0\pi^0$) final states. The last two modes have been added since Ref. [4]. There are several other significant changes in the analysis. Improvements in track and K_S^0 reconstruction efficiency in 2001 data produce an approximately 30% increase in the yields for a given luminosity. Better alignment of the tracking systems in 2001 data and improvements in the tagging vertex reconstruction algorithm increase the sensitivity of the measurement by an additional 10%. Optimization of the $J/\psi K_L^0$ selection increases the purity of this sample. The final B_{CP} sample contains about 640 signal events and, with all the improvements, the statistical power of the analysis is almost doubled with respect to that of Ref. [4].

We examine each of the events in the B_{CP} sample for evidence that the other neutral B meson decayed as a B^0 or a $\overline{B}^0$ (flavor tag). The decay-time distributions for events with a B^0 or a $\overline{B}^0$ tag can be expressed in terms of a complex parameter λ that depends on both $B^0\overline{B}^0$ mixing and on the amplitudes describing $\overline{B}^0$ and B^0 decay to a common final state f [8]. The distribution $f_+(f_-)$ of the decay rate when the tagging meson is a $B^0(\overline{B}^0)$ is given by

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}(1 + |\lambda|^2)} \times \left[\frac{1 + |\lambda|^2}{2} \pm \mathrm{Im}\lambda \sin(\Delta m_{B^0}\Delta t) \mp \frac{1 - |\lambda|^2}{2}\cos(\Delta m_{B^0}\Delta t)\right], \tag{1}$$

where $\Delta t = t_{CP} - t_{\text{tag}}$ is the time between the two B decays, τ_{B^0} is the B^0 lifetime, and Δm_{B^0} is the mass difference determined from $B^0\overline{B}^0$ mixing [9]. The first oscillatory term in Eq. (1) is due to interference between direct decay and decay after mixing, and the second term is due to direct CP violation. A difference between the B^0 and $\overline{B}^0$ Δt distributions or a Δt asymmetry for either flavor tag is evidence for CP violation.

In the standard model $\lambda = \eta_f e^{-2i\beta}$ for charmonium-containing $b \to c\bar{c}s$ decays, η_f is the CP eigenvalue of the state f and $\beta = \arg[-V_{\text{cd}}V_{\text{cb}}^*/V_{\text{td}}V_{\text{tb}}^*]$ is an angle of the unitarity triangle of the three-generation CKM matrix [2]. Thus, the time-dependent CP-violating asymmetry is

$$\begin{aligned} A_{CP}(\Delta t) &\equiv \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} \\ &= -\eta_f \sin 2\beta \sin(\Delta m_{B^0}\Delta t), \end{aligned} \tag{2}$$

where $\eta_f = -1$ for $J/\psi K_S^0$, $\psi(2S)K_S^0$, and $\chi_{c1}K_S^0$ and $+1$ for $J/\psi K_L^0$. Because of the presence of even ($L = 0, 2$) and odd ($L = 1$) orbital angular momenta in the $J/\psi K^{*0}$ ($K^{*0} \to K_S^0\pi^0$) system, there are 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 dilution factor $D_\perp = 1 - 2R_\perp$, where $R_\perp$ is the fraction of the $L = 1$ component. We have measured $R_\perp = (16 \pm 3.5)\%$ [10] which, after acceptance corrections, leads to an effective $\eta_f = 0.65 \pm 0.07$ for the $J/\psi K^{*0}$ mode.

The hadronic event selection, lepton and charged kaon identification, and J/ψ and $\psi(2S)$ reconstruction relevant to this analysis have been described in Ref. [4], as have the selection criteria for the channels $J/\psi K_S^0$ ($K_S^0 \to \pi^+\pi^-, \pi^0\pi^0$), $\psi(2S)K_S^0$ ($K_S^0 \to \pi^+\pi^-$), and $J/\psi K_L^0$. In the $J/\psi K_L^0$ selection, the transverse missing momentum requirement has been reoptimized for the A_{CP} study.

For the decay $B^0 \to \chi_{c1}K_S^0$, the mode $\chi_{c1} \to J/\psi\gamma$ is reconstructed with mass-constrained J/ψ candidates selected as in other charmonium channels [4]. Photons must have an energy greater than 150 MeV and must not be associated with any reconstructed π^0. The resulting $J/\psi\gamma$ mass is required to be within 35 MeV/c^2 of the χ_{c1} mass [9].

For the decay $B^0 \to J/\psi K^{*0}$, the $K^{*0} \to K_S^0\pi^0$ candidate is formed by combining a $\pi^0 \to \gamma\gamma$ candidate satisfying $106 \le m_{\gamma\gamma} \le 153$ MeV/c^2 with a K_S^0 candidate. The cosine of the angle between the K_S^0 momentum vector in the K^{*0} rest frame and the K^{*0} momentum defined in the B rest frame is required to be less than 0.95. We require $796 \le m_{K_S^0\pi^0} \le 996$ MeV/c^2.

B_{CP} candidates are selected by requiring that the difference ΔE between their energy and the beam energy in the center-of-mass frame be less than 3σ from zero. For modes involving K_S^0, the beam-energy substituted mass $m_{\rm ES} = \sqrt{(E_{\rm beam}^{\rm cm})^2 - (p_B^{\rm cm})^2}$ must be greater than 5.2 GeV/c^2. The resolution for ΔE is about 10 MeV, except for the $K_S^0 \to \pi^0\pi^0$ mode (33 MeV), the $J/\psi K^{*0}$ mode (20 MeV), and the $J/\psi K_L^0$ mode (3.5 MeV after B mass constraint). For the purpose of determining numbers of events and purities, a signal region $m_{\rm ES} > 5.27$ GeV/c^2 is used for all modes except $J/\psi K_L^0$ and $J/\psi K^{*0}$.

Figure 1 shows the resulting $m_{\rm ES}$ distributions for B_{CP} candidates containing a K_S^0 and the ΔE distribution for the candidates containing a K_L^0. The B_{CP} sample contains 1230 events in the signal region (before tag and vertex requirements), with an estimated background of 200 events, predominantly in the $J/\psi K_L^0$ channel. For that channel, the composition, effective η_f, and ΔE distributions of the individual background sources are taken either from a Monte Carlo simulation (for B decays to J/ψ) or from the $m_{\ell^+\ell^-}$ sidebands in data.

A measurement of A_{CP} requires a determination of the experimental Δt resolution and the fraction of events in which the tag assignment is incorrect. A mistag fraction w reduces the observed asymmetry by a factor of $(1 - 2w)$. A sample of self-tagging B decays $B_{\rm flav}$ used in the determination of the mistag fractions and Δt resolution functions consists of the channels $D^{(*)-}h^+$ ($h^+ = \pi^+, \rho^+, a_1^+$) and $J/\psi K^{*0}$ ($K^{*0} \to K^+\pi^-$) [11]. A control sample of charged B mesons decaying to the final states $J/\psi K^{(*)+}$, $\psi(2S)K^+$, $\chi_{c1}K^+$, and $\overline{D}^{(*)0}\pi^+$ is used for validation studies.

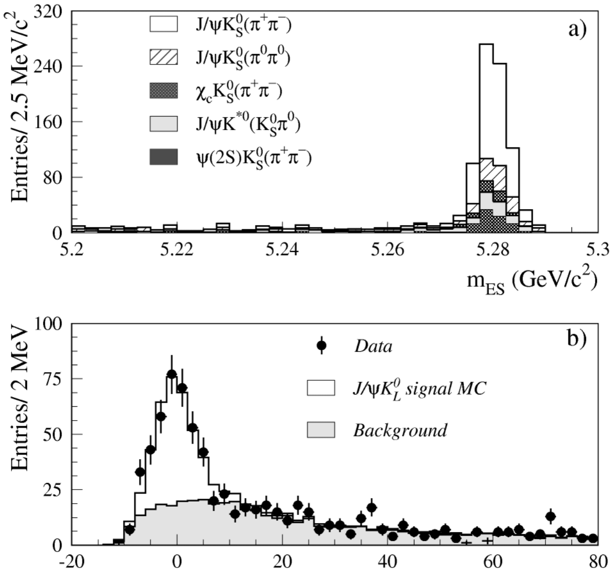

FIG. 1. (a) Distribution of $m_{\rm ES}$ for B_{CP} candidates having a K_S^0 in the final state; (b) distribution of ΔE for $J/\psi K_L^0$ candidates.

For flavor tagging, we exploit information from the other B decay in the event. Each event is assigned to one of four hierarchical, mutually exclusive tagging categories or excluded from further analysis. The Lepton and Kaon categories contain events with high momentum leptons from semileptonic B decays or with kaons whose charge is correlated with the flavor of the decaying b quark (e.g., a positive lepton or kaon yields a B^0 tag). The NT1 and NT2 categories are based on a neural network algorithm whose tagging power arises primarily from soft pions from D^{*+} decays and from recovering unidentified isolated primary leptons [4].

The numbers of tagged events are shown in Table I as are the signal purities. Purities are determined from fits to the $m_{\rm ES}$ (all K_S^0 modes except K^{*0}) or ΔE (K_L^0 mode) distributions in data or from Monte Carlo simulation (K^{*0} mode). The efficiencies and mistag fractions for the four tagging categories are measured from data and summarized in Table II.

The time interval Δt between the two B decays is then determined from the separation along the boost direction $\Delta z = z_{CP} - z_{\rm tag}$, including an event-by-event correction for the direction of the B with respect to the z direction in the $\Upsilon(4S)$ frame. z_{CP} is determined from the charged tracks that constitute the B_{CP} candidate. The tagging vertex is determined by fitting the tracks not belonging to the B_{CP} (or $B_{\rm flav}$) candidate to a common vertex. The method employed is identical to our previous analysis except for the addition of a constraint from knowledge of the beam spot location and beam direction. This constraint is incorporated through the addition of a pseudotrack to the tagging vertex, computed from the B_{CP} ($B_{\rm flav}$) vertex and three-momentum, the beam spot (with a vertical size of 10 μm), and the $\Upsilon(4S)$ momentum. The Δz reconstruction efficiency is 97%. For 99% of the reconstructed vertices the rms Δz resolution measured in data is 180 μm, dominated by the $z_{\rm tag}$ vertex. An accepted candidate must have a converged fit for the B_{CP} and $B_{\rm tag}$ vertices, an error of less than 400 μm on Δz, and a measured $|\Delta t| < 20$ ps. After tag and vertexing requirements about 640 signal events remain.

The $\sin 2\beta$ measurement is made with a simultaneous unbinned maximum likelihood fit to the Δt distributions of the B_{CP} and $B_{\rm flav}$ tagged samples. The Δt distribution of the former is given by Eq. (1), with $|\lambda| = 1$. The $B_{\rm flav}$ sample evolves according to the known rate for flavor oscillations in neutral B mesons [9]. The amplitudes for B_{CP} asymmetries and for $B_{\rm flav}$ flavor oscillations are reduced by the same factor $(1 - 2w)$ due to wrong tags. Both distributions are convolved with a common Δt resolution function and backgrounds are accounted for by adding terms to the likelihood, incorporated with different assumptions about their Δt evolution and convolved with a separate resolution function. Events are assigned signal and background probabilities based on the $m_{\rm ES}$ (all modes except $J/\psi K_L^0$) or ΔE ($J/\psi K_L^0$) distributions.

TABLE I. Number of tagged events, signal purity, and result of fitting for CP asymmetries in the full CP sample and in various subsamples, as well as in the B_{flav} and charged B control samples. Errors are statistical only.

Sample	N_{tag}	Purity (%)	$\sin 2\beta$
$J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$	480	96	0.56 ± 0.15
$J/\psi K_L^0$ $(\eta_f = +1)$	273	51	0.70 ± 0.34
$J/\psi K^{*0}$, $K^{*0} \to K_S^0\pi^0$	50	74	0.82 ± 1.00
Full CP sample	803	80	0.59 ± 0.14
$J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$ only $(\eta_f = -1)$			
$J/\psi K_S^0$ $(K_S^0 \to \pi^+\pi^-)$	316	98	0.45 ± 0.18
$J/\psi K_S^0$ $(K_S^0 \to \pi^0\pi^0)$	64	94	0.70 ± 0.50
$\psi(2S)K_S^0$ $(K_S^0 \to \pi^+\pi^-)$	67	98	0.47 ± 0.42
$\chi_{c1}K_S^0$	33	97	$2.59 \pm {}^{0.55}_{0.67}$
Lepton tags	74	100	0.54 ± 0.29
Kaon tags	271	98	0.59 ± 0.20
NT1 tags	46	97	0.67 ± 0.45
NT2 tags	89	95	0.10 ± 0.74
B^0 tags	234	98	0.50 ± 0.22
$\overline{B}^0$ tags	246	97	0.61 ± 0.22
B_{flav} non-CP sample	7591	86	0.02 ± 0.04
Charged B non-CP sample	6814	86	0.03 ± 0.04

The representation of the Δt resolution function is the same as in [4] with small changes: all offsets are modeled to be proportional to $\sigma_{\Delta t}$, which is correlated with the weight that the daughters of long-lived charm particles have in the tag vertex reconstruction. Separate resolution functions have been used for the data collected in 1999–2000 and 2001, due to the significant improvement in the silicon vertex tracker (SVT) alignment. The scale factor for the tail component is fixed to the Monte Carlo value since it is strongly correlated with the other resolution function parameters.

A total of 45 parameters are varied in the likelihood fit, including $\sin 2\beta$ (1), the average mistag fraction w and the difference Δw between B^0 and $\overline{B}^0$ mistags for each tagging category (8), parameters for the signal Δt resolution (16), and parameters for background time dependence (9), Δt resolution (3), and mistag fractions (8). The determination of the mistag fractions and signal Δt resolution function is dominated by the large B_{flav} sample. Background parameters are governed by events with $m_{\mathrm{ES}} < 5.27\ \mathrm{GeV}/c^2$. As a result, the largest correlation between $\sin 2\beta$ and any linear combination of the other free parameters is only 0.13. We fix $\tau_{B^0} = 1.548$ ps and $\Delta m_{B^0} = 0.472\hbar\ \mathrm{ps}^{-1}$ [9]. The value of $\sin 2\beta$ and the CP asymmetry in the Δt distribution were once more hidden, following publication of our result in Ref. [4], until the event selection was optimized and all other aspects of the present analysis were complete.

Figure 2 shows the Δt distributions and A_{CP} as a function of Δt overlaid with the likelihood fit result for the $\eta_f = -1$ and $\eta_f = +1$ samples. The probability of obtaining a lower likelihood, evaluated with a parametrized simulation of a large number of data-sized experiments, is 27%. The simultaneous fit to all CP decay modes and flavor decay modes yields

$$\sin 2\beta = 0.59 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{syst})\,.$$

Repeating the fit with all parameters except $\sin 2\beta$ fixed to their values at the global maximum likelihood, we

TABLE II. Average mistag fractions w_i and mistag differences $\Delta w_i = w_i(B^0) - w_i(\overline{B}^0)$ extracted for each tagging category i from the maximum-likelihood fit to the time distribution for the fully reconstructed B^0 sample ($B_{\mathrm{flav}} + B_{CP}$). The figure of merit for tagging is the effective tagging efficiency $Q_i = \varepsilon_i(1 - 2w_i)^2$, where ε_i is the fraction of events with a reconstructed tag vertex that are assigned to the ith category. Uncertainties are statistical only. The statistical error on $\sin 2\beta$ is proportional to $1/\sqrt{Q}$, where $Q = \sum Q_i$.

Category	ε (%)	w (%)	Δw (%)	Q (%)
Lepton	10.9 ± 0.3	8.9 ± 1.3	0.9 ± 2.2	7.4 ± 0.5
Kaon	35.8 ± 0.5	17.6 ± 1.0	-1.9 ± 1.5	15.0 ± 0.9
NT1	7.8 ± 0.3	22.0 ± 2.1	5.6 ± 3.2	2.5 ± 0.4
NT2	13.8 ± 0.3	35.1 ± 1.9	-5.9 ± 2.7	1.2 ± 0.3
All	68.4 ± 0.7			26.1 ± 1.2

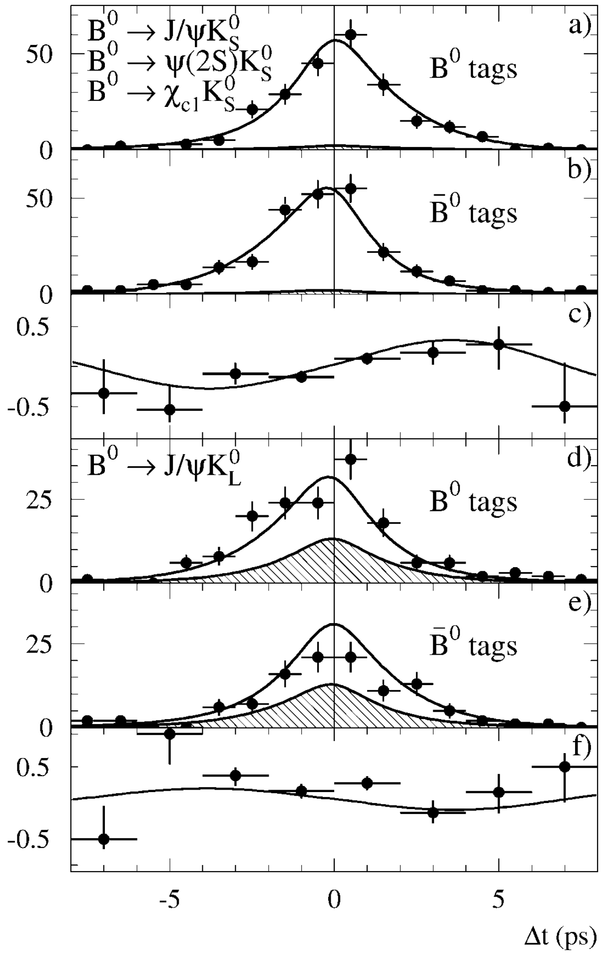

FIG. 2. Number of $\eta_f = -1$ candidates [$J/\psi K_S^0$, $\psi(2S)K_S^0$, and $\chi_{c1}K_S^0$] in the signal region (a) with a B^0 tag N_{B^0} and (b) with a $\overline{B}^0$ tag $N_{\overline{B}^0}$, and (c) the asymmetry $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt. The solid curves represent the result of the combined fit to all selected CP events; the shaded regions represent the background contributions. (d)–(f) The corresponding information for the $\eta_f = +1$ mode ($J/\psi K_L^0$). The likelihood is normalized to the total number of B^0 and $\overline{B}^0$ tags. The value of $\sin 2\beta$ is independent of the individual normalizations and therefore of the difference between the number of B^0 and $\overline{B}^0$ tags.

attribute a total contribution in quadrature of 0.02 to the error on $\sin 2\beta$ due to the combined statistical uncertainties in mistag fractions, Δt resolution, and background parameters. The dominant sources of systematic error are the parametrization of the Δt resolution function (0.03), due in part to residual uncertainties in SVT alignment, possible differences in the mistag fractions between the B_{CP} and $B_{\rm flav}$ samples (0.03), and uncertainties in the level, composition, and CP asymmetry of the background in the selected CP events (0.02). The systematic errors from uncertainties in Δm_{B^0} and τ_{B^0} and from the parametrization of the background in the $B_{\rm flav}$ sample are small; an increase of $0.02\hbar$ ps^{-1} in the value for Δm_{B^0} decreases $\sin 2\beta$ by 0.015.

The large sample of reconstructed events 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 subsamples are shown in Table I. The consistency between the six CP modes is satisfactory, the probability of finding a worse agreement being 8%. The observed asymmetry in the number of B^0 (160) and $\overline{B}^0$ (113) tags in the $J/\psi K_L^0$ sample has no impact on the $\sin 2\beta$ measurement. Table I also shows results of fits to the samples of non-CP decay modes, where no statistically significant asymmetry is found. Performing the current analysis on the previously published data sample and decay modes yields a value of $\sin 2\beta = 0.32 \pm 0.18$, consistent with the published value [4]. For only these decay modes, the year 2001 data yield $\sin 2\beta = 0.83 \pm 0.23$, consistent with the 1999–2000 results at the 1.8σ level; for the $J/\psi K_S^0$ ($K_S^0 \to \pi^+\pi^-$) channel the consistency is at the 1.4σ level.

If $|\lambda|$ is allowed to float in the fit to the $\eta_f = -1$ sample, which has high purity and requires minimal assumptions on the effect of backgrounds, the value obtained is $|\lambda| = 0.93 \pm 0.09({\rm stat}) \pm 0.03({\rm syst})$. The sources of the systematic error in this measurement are the same as in the $\sin 2\beta$ analysis. In this fit, the coefficient of the $\sin(\Delta m_{B^0}\Delta t)$ term in Eq. (1) is measured to be $\sin 2\beta = 0.56 \pm 0.4({\rm stat})$, in agreement with Table I.

The measurement of $\sin 2\beta = 0.59 \pm 0.14({\rm stat}) \pm 0.05({\rm syst})$ reported here establishes CP violation in the B^0 meson system at the 4.1σ level. This significance is computed from the sum in quadrature of the statistical and additive systematic errors. The probability of obtaining this value or higher in the absence of CP violation is less than 3×10^{-5}. The corresponding probability for the $\eta_f = -1$ modes alone is 2×10^{-4}. This direct measurement is consistent with the range implied by measurements and theoretical estimates of the magnitudes of CKM matrix elements [12].

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