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Measurement of decay amplitudes of $B \rightarrow J/\psi K^*$, $\psi(2S)K^*$, and $\chi_{c1}K^*$ with an angular analysis

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We perform the first three-dimensional measurement of the amplitudes of $B \rightarrow \psi(2S)K^*$ and $B \rightarrow \chi_{c1}K^*$ decays and update our previous measurement for $B \rightarrow J/\psi K^*$. We use a data sample collected with the *BABAR* detector at the PEP-II storage ring, corresponding to 232×10^6 $B\bar{B}$ pairs. The longitudinal polarization of decays involving a $J^{PC} = 1^{++}$ χ_{c1} meson is found to be larger than that with a 1^{--} J/ψ or $\psi(2S)$ meson. No direct CP -violating charge asymmetry is observed.

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In the context of measuring the parameters of the unitarity triangle of the Cabibbo-Kobayashi-Maskawa matrix, B^0 decays to charmonium-containing final states ($J/\psi, \psi(2S), \chi_{c1}$) K^* , defined collectively here as $B^0 \rightarrow (c\bar{c})K^*$, are of interest for the precise measurement of $\sin 2\beta$, where $\beta \equiv \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$, in a similar way as for $B^0 \rightarrow J/\psi K^0$. Furthermore, the $J/\psi K^*$ channel allows the measurement of $\cos 2\beta$ [1].

For the modes considered in this paper, the final state consists of two spin-1 mesons, leading to three possible values of the total angular momentum with different CP eigenvalues ($L=1$ is odd, while $L=0, 2$ are even). The different contributions must be taken into account in the measurement of $\sin 2\beta$. The amplitude for longitudinal polarization of the two spin-1 mesons is A_0 . There are two amplitudes for polarizations of the mesons transverse to the decay axis, here expressed in the transversity basis [2]: A_{\parallel} for parallel polarization and A_{\perp} for their perpendicular polarization. Only the relative amplitudes are measured, so that $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$. Previous measurements by the CLEO [3], CDF [4], *BABAR* [1], and Belle [5] collaborations for the $B \rightarrow J/\psi K^*$ channels are all compatible with each other, and with a CP -odd intensity fraction $|A_{\perp}|^2$ close to 0.2.

Factorization predicts that the phases of the transversity decay amplitudes are the same. *BABAR* has observed [1,6] a significant departure from this prediction.

Precise measurements of the branching fractions of $B \rightarrow (c\bar{c})K^*$ decays are now available [7] to test the theoretical description of the nonfactorizable contributions [8], but polarization measurements are also needed. In particular, measurements for $\psi(2S)$ and χ_{c1} , compared to that of J/ψ , would discriminate the mass dependence from the quantum number dependence. CLEO has measured the longitudinal polarization of $B \rightarrow \psi(2S)K^*$ decays to be $|A_0|^2 = 0.45 \pm 0.11 \pm 0.04$ [9]. Belle has studied $B \rightarrow \chi_{c1}K^*$ decays and obtained $|A_0|^2 = 0.87 \pm 0.09 \pm 0.07$ [10].

The decays $B \rightarrow (c\bar{c})K^{(*)}$ provide a clean environment for the measurement of the Cabibbo-Kobayashi-Maskawa angle β because one tree amplitude dominates the decay. Very small direct CP -violating charge asymmetries are expected in these decays, and no such signal has been found [7]. While more than one amplitude with different strong and weak phases are needed to create a charge asymmetry in a simple branching fraction measurement, London *et al.* have suggested [11] that an angular analysis of vector-vector decays can detect charge asymmetries

even in the case of vanishing strong phase difference. Belle has looked for, and not found, such a signal [5].

In this paper we present the amplitude measurement of charged and neutral $B \rightarrow (c\bar{c})K^*$ using a selection similar to that of Ref. [7], and a fitting method similar to that of Ref. [1]. We use the notation ψ for the 1^{--} states J/ψ and $\psi(2S)$. $\psi(\chi_{c1})$ candidates are reconstructed in their decays to $\ell^+\ell^-(J/\psi\gamma)$, where ℓ represents an electron or a muon. Decays to the flavor eigenstates $K^{*0} \rightarrow K^{\pm}\pi^{\mp}$, $K^{*\pm} \rightarrow K_S^0\pi^{\pm}$, and $K^{*\pm} \rightarrow K^{\pm}\pi^0$ are used. The relative strong phases are known to have a twofold ambiguity when measured in an angular analysis alone. In contrast to earlier publications [3,4,6] we use here the set of phases predicted in Ref. [12], with arguments based on the conservation of the s -quark helicity in the decay of the b quark. We have confirmed experimentally this prediction through the study of the variation with $K\pi$ invariant mass of the phase difference between the $K^*(892)$ amplitude and a nonresonant $K\pi$ S -wave amplitude [1].

The data were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring, and correspond to an integrated luminosity of about 209 fb^{-1} at the center-of-mass energy near the $Y(4S)$ mass. The *BABAR* detector is described in detail elsewhere [13]. Charged-particle tracking is provided by a five-layer silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). For charged-particle identification (PID), ionization energy loss in the DCH and SVT, and Cherenkov radiation detected in a ring-imaging device (DIRC) are used. Photons are identified by the electromagnetic calorimeter (EMC), which comprises 6580 thallium-doped CsI crystals. These systems are mounted inside a 1.5-T solenoidal superconducting magnet. Muons are identified in the instrumented flux return (IFR), composed of resistive plate chambers and layers of iron that return the magnetic flux of the solenoid. We use the GEANT4 [14] software to simulate interactions of particles traversing the detector, taking into account the varying accelerator and detector conditions.

Candidates for $J/\psi \rightarrow e^+e^-(\mu^+\mu^-)$ must have a mass in the range 2.95–3.14 (3.06–3.14) GeV/c^2 . $\psi(2S)$ candidates are required to have invariant masses $3.44 < m_{e^+e^-} < 3.74 \text{ GeV}/c^2$ or $3.64 < m_{\mu^+\mu^-} < 3.74 \text{ GeV}/c^2$. Electron candidates are combined with photon candidates in order to recover some of the energy lost through Bremsstrahlung. J/ψ candidates and γ candidates with an energy larger than 150 MeV are combined to form χ_{c1} candidates, which must satisfy $350 < m_{\ell^+\ell^-\gamma} - m_{\ell^+\ell^-} < 450 \text{ MeV}/c^2$.

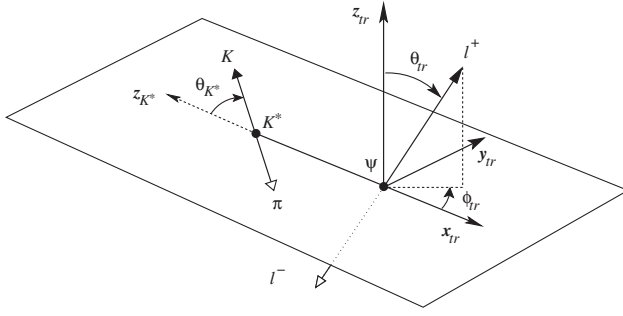


FIG. 1. Definition of the transversity angles. Details are given in the text.

$\pi^0 \rightarrow \gamma\gamma$ candidates must satisfy $113 < m_{\gamma\gamma} < 153$ MeV/ c^2 . The energy of each photon has to be greater than 50 MeV. $K_S^0 \rightarrow \pi^+\pi^-$ candidates are required to satisfy $489 < m_{\pi^+\pi^-} < 507$ MeV/ c^2 . In addition, the K_S^0 flight distance from the ψ vertex must be larger than 3 times its uncertainty. K^{*0} and K^{*+} candidates are required to satisfy $796 < m_K\pi < 996$ MeV/ c^2 and $792 < m_K\pi < 992$ MeV/ c^2 , respectively. In addition, due to the presence of a large background of low-energy nongenuine π^0 's, the cosine of the angle θ_{K^*} between the K momentum and the B momentum in the K^* rest frame has to be less than 0.8 for $K^* \rightarrow K^\pm\pi^0$. In events where two B 's reconstruct to modes with the same $c\bar{c}$ and K candidate, one with a π^\pm and the other with a π^0 , the B candidate with a π^0 is discarded due to the high background induced by fake π^0 's.

B candidates, reconstructed by combining $c\bar{c}$ and K^* candidates, are characterized by two kinematic variables: the difference between the reconstructed energy of the B candidate and the beam energy in the center-of-mass frame $\Delta E = E_B^* - \sqrt{s}/2$, and the beam-energy substituted mass $m_{ES} \equiv \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)/E_0^2 - \mathbf{p}_B^2}$, where the subscripts 0 and B correspond to $Y(4S)$ and the B candidate in the laboratory frame. For a correctly reconstructed B meson, ΔE is expected to peak near zero and m_{ES} near the B -meson mass 5.279 GeV/ c^2 . The analysis is performed in a region of the m_{ES} vs ΔE plane defined by $5.2 < m_{ES} < 5.3$ GeV/ c^2 and $-120 < \Delta E < 120$ MeV. The signal re-

gion is defined as $m_{ES} > 5.27$ GeV/ c^2 and $|\Delta E|$ smaller than 40 (30) MeV for channels with (without) a π^0 . For events that have multiple candidates, the candidate having the smallest $|\Delta E|$ is chosen. m_{ES} distributions are available in Ref. [15].

The B decay amplitudes are measured from the differential decay distribution, expressed in the transversity basis [1,6], Fig. 1, with conventions detailed in Ref. [16]. θ_{K^*} is the helicity angle of the K^* decay. It is defined in the rest frame of the K^* meson and is the angle between the kaon and the opposite direction of the B meson in this frame. θ_{tr} and ϕ_{tr} are defined in the $\psi(\chi_{c1})$ rest frame and are the polar and azimuthal angle of the positive lepton (J/ψ daughter of χ_{c1}), with respect the axis defined by

- (i) \mathbf{x}_{tr} : opposite direction of the B meson;
- (ii) \mathbf{y}_{tr} : perpendicular to \mathbf{x}_{tr} , in the $(\mathbf{x}_{tr}, \mathbf{p}_{K^*})$ plane, with a direction such that $\mathbf{p}_{K^*} \cdot \mathbf{x}_{tr} > 0$;
- (iii) \mathbf{z}_{tr} : to complete the frame, i.e., $\mathbf{z}_{tr} = \mathbf{x}_{tr} \times \mathbf{y}_{tr}$.

In terms of the transversity angular variables $\boldsymbol{\omega} \equiv (\cos\theta_{K^*}, \cos\theta_{tr}, \phi_{tr})$, the time-integrated differential decay rate for the decay of the B meson is

$$g(\boldsymbol{\omega}; \mathbf{A}) \equiv \frac{1}{\Gamma} \frac{d^3\Gamma}{d\cos\theta_{K^*}d\cos\theta_{tr}d\phi_{tr}} = \sum_{k=1}^6 \mathcal{A}_k f_k(\boldsymbol{\omega}), \quad (1)$$

where the amplitude coefficients \mathcal{A}_i and the angular functions $f_k(\boldsymbol{\omega})$, $k = 1, \dots, 6$ are listed in Table I. The ψ decays to two spin-1/2 particles, while the χ_{c1} decays to two vector particles. The angular dependencies are therefore different [16]. The symbol $\mathbf{A} \equiv (A_0, A_{\parallel}, A_{\perp})$ denotes the transversity amplitudes for the decay of the B meson, and $\bar{\mathbf{A}}$ for the \bar{B} meson decay. In the absence of direct CP violation, we can choose a phase convention in which these amplitudes are related by $\bar{A}_0 = +A_0$, $\bar{A}_{\parallel} = +A_{\parallel}$, $\bar{A}_{\perp} = -A_{\perp}$, so that A_{\perp} is CP odd and A_0 and A_{\parallel} are CP even. The phases δ_j of the amplitudes, where $j = 0, \parallel, \perp$, are defined by $A_j = |A_j|e^{i\delta_j}$. Phases are defined relative to $\delta_0 = 0$.

We perform an unbinned likelihood fit of the three-dimensional angle probability density function (PDF). The acceptance of the detector and the efficiency of the event reconstruction may vary as a function of the transversity angles, in particular, as the angle θ_{K^*} is strongly

TABLE I. Amplitude coefficients \mathcal{A}_k and angular functions $f_k(\boldsymbol{\omega})$ that contribute to the differential decay rate. An overall normalization factor $9/32\pi$ (for ψ) and $9/64\pi$ (for χ_{c1}) has been omitted. In the case of a \bar{B} decay, the Im terms change sign.

i	\mathcal{A}_k	$f_k(\boldsymbol{\omega})$ for ψ [1,6]	$f_k(\boldsymbol{\omega})$ for χ_{c1} [16]
1	$ A_0 ^2$	$2\cos^2\theta_{K^*}[1 - \sin^2\theta_{tr}\cos^2\phi_{tr}]$	$2\cos^2\theta_{K^*}[1 + \sin^2\theta_{tr}\cos^2\phi_{tr}]$
2	$ A_{\parallel} ^2$	$\sin^2\theta_{K^*}[1 - \sin^2\theta_{tr}\sin^2\phi_{tr}]$	$\sin^2\theta_{K^*}[1 + \sin^2\theta_{tr}\sin^2\phi_{tr}]$
3	$ A_{\perp} ^2$	$\sin^2\theta_{K^*}\sin^2\theta_{tr}$	$\sin^2\theta_{K^*}[2\cos^2\theta_{tr} + \sin^2\theta_{tr}]$
4	$\text{Im}(A_{\parallel}^*A_{\perp})$	$\sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}$	$-\sin^2\theta_{K^*}\sin 2\theta_{tr}\sin\phi_{tr}$
5	$\text{Re}(A_{\parallel}^*A_0)$	$-\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr}$	$\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin^2\theta_{tr}\sin 2\phi_{tr}$
6	$\text{Im}(A_{\perp}^*A_0)$	$\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos\phi_{tr}$	$-\frac{1}{\sqrt{2}}\sin 2\theta_{K^*}\sin 2\theta_{tr}\cos\phi_{tr}$

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correlated with the momentum of the final kaon and pion. We use the acceptance correction method developed in Ref. [1]. The PDF of the observed events, g_{obs} , is

$$g_{\text{obs}}(\boldsymbol{\omega}; \mathbf{A}) = g(\boldsymbol{\omega}; \mathbf{A}) \frac{\varepsilon(\boldsymbol{\omega})}{\langle \varepsilon \rangle(\mathbf{A})}, \quad (2)$$

where $\varepsilon(\boldsymbol{\omega})$ is the angle-dependent acceptance and

$$\langle \varepsilon \rangle(\mathbf{A}) \equiv \int g(\boldsymbol{\omega}; \mathbf{A}) \varepsilon(\boldsymbol{\omega}) d\boldsymbol{\omega} \quad (3)$$

is the average acceptance. We take into account the presence of cross feed from channels with the same $c\bar{c}$ candidate and a different K^* candidate that has (due to isospin symmetry) the same \mathbf{A} dependence as the signal. The observed PDF for channel b ($b = K^\pm \pi^\mp, K_S^0 \pi^\pm, K^\pm \pi^0$) is then

$$g_{\text{obs}}^b(\boldsymbol{\omega}; \mathbf{A}) = g(\boldsymbol{\omega}; \mathbf{A}) \frac{\varepsilon^b(\boldsymbol{\omega})}{\sum_{k=1}^6 \mathcal{A}_k(\mathbf{A}) \Phi_k^b}, \quad (4)$$

where $\varepsilon^b(\boldsymbol{\omega})$ is the efficiency, defined as the ratio between the reconstructed and generated yield for the process ($B \rightarrow (c\bar{c})K^*, K^* \rightarrow b$), and we do not distinguish between correctly reconstructed signal and cross feed in the numerator

$$\varepsilon^b(\boldsymbol{\omega}) \equiv \sum_a F_a \varepsilon^{a \rightarrow b}(\boldsymbol{\omega}). \quad (5)$$

$\varepsilon^{a \rightarrow b}(\boldsymbol{\omega})$ is the probability for an event generated in channel a and with angle $\boldsymbol{\omega}$ to be detected as an event in channel b . F_a , $a = K_S^0 \pi^0, K^\pm \pi^\mp, K^\pm \pi^0, K_S^0 \pi^\pm$, denotes the fraction of each channel in the total branching fraction $B \rightarrow c\bar{c}K^*$, $\sum_a F_a = 1$. The Φ_k^b are the $f_k(\boldsymbol{\omega})$ moments of the total efficiency ε^b , including cross feed:

$$\Phi_k^b \equiv \sum_a F_a \int f_k(\boldsymbol{\omega}) \varepsilon^{a \rightarrow b}(\boldsymbol{\omega}) d\boldsymbol{\omega}. \quad (6)$$

Under the approximations of neglecting the angular resolution for signal and cross-feed events, and the possible mismeasurement of the B flavor such as in events where both daughters in $K^{*0} \rightarrow K^\pm \pi^\mp$ are misidentified (K - π swap), the PDF g_{obs} can be expressed as in Eq. (2), and only the coefficients Φ_k^b are needed. The biases induced by these approximations have been estimated with Monte Carlo (MC) based studies and found to be negligible.

The coefficients Φ_k^b are computed with exclusive signal MC samples obtained using a full simulation of the experiment [14,17]. PID efficiencies measured with data control samples are used to adjust the MC simulation to the

observed performance of the detector. Separate coefficients are used for different charges of the final state mesons, in particular, to take into account the charge dependence of the interaction of charged kaons with matter, and a possible charge asymmetry of the detector. Writing the expression for the log-likelihood $L^b(\mathbf{A})$ for the PDF $g_{\text{obs}}^b(\boldsymbol{\omega}_i; \mathbf{A})$ for a pure signal sample of N_S events, the relevant contribution is

$$L^b(\mathbf{A}) = \sum_{i=1}^{N_S} \ln(g(\boldsymbol{\omega}_i; \mathbf{A})) - N_S \ln\left(\sum_k \mathcal{A}_k(\mathbf{A}) \Phi_k^b\right), \quad (7)$$

since the remaining term $\sum_{i=1}^{N_S} \ln(\varepsilon^b(\boldsymbol{\omega}_i))$ does not depend on the amplitudes.

We use a background correction method [1] in which background events from a pure background sample of N_B events are added with a negative weight to the log-likelihood that is maximized,

$$L^b(\mathbf{A}) \equiv \sum_{i=1}^{n_B + N_S} L(\boldsymbol{\omega}_i; \mathbf{A}) - \frac{\tilde{n}_B}{N_B} \sum_{j=1}^{N_B} L(\boldsymbol{\omega}_j; \mathbf{A}), \quad (8)$$

where $L(\boldsymbol{\omega}; \mathbf{A}) = \ln(g_{\text{obs}}^b(\boldsymbol{\omega}; \mathbf{A}))$. The fit is performed within the m_{ES} signal region. Background events used here for subtraction are from generic ($B\bar{B}, q\bar{q}$) MC samples. \tilde{n}_B is an estimate of the unknown number n_B of background events that are present in the signal region in the data sample.

As L^b is not a log-likelihood, the uncertainties yielded by the minimization program MINUIT [18] are biased estimates of the actual uncertainties. An unbiased estimation of the uncertainties is described and validated in Appendix A of Ref. [1]. With this pseudo-log-likelihood technique, we avoid parametrizing the acceptance as well as the background angular distributions.

The measurement is affected by several systematic uncertainties. The branching fractions used in the cross-feed part of the acceptance cross section are varied by $\pm 1\sigma$, and the largest variation is retained. The uncertainty induced by the finite size of the MC sample used to compute the coefficients Φ_k^b is estimated by the statistical uncertainty of the angular fit on that MC sample [6]. The uncertainty due to our limited understanding of the PID efficiency is estimated by using two different methods to correct for the MC-vs-data differences. The background uncertainty is obtained by comparing MC and data shapes of the m_{ES} distributions for the combinatorial component and by using the corresponding branching errors for the peaking com-

TABLE II. Summary of the measured amplitudes. For decays to χ_{c1} , as A_\perp is compatible with zero, its phase is not defined.

Channel	$ A_0 ^2$	$ A_{\parallel} ^2$	$ A_\perp ^2$	δ_{\parallel}	δ_\perp
$J/\psi K^*$	$0.556 \pm 0.009 \pm 0.010$	$0.211 \pm 0.010 \pm 0.006$	$0.233 \pm 0.010 \pm 0.005$	$-2.93 \pm 0.08 \pm 0.04$	$2.91 \pm 0.05 \pm 0.03$
$\psi(2S) K^*$	$0.48 \pm 0.05 \pm 0.02$	$0.22 \pm 0.06 \pm 0.02$	$0.30 \pm 0.06 \pm 0.02$	$-2.8 \pm 0.4 \pm 0.1$	$2.8 \pm 0.3 \pm 0.1$
$\chi_{c1} K^*$	$0.77 \pm 0.07 \pm 0.04$	$0.20 \pm 0.07 \pm 0.04$	$0.03 \pm 0.04 \pm 0.02$	$0.0 \pm 0.3 \pm 0.1$	\dots

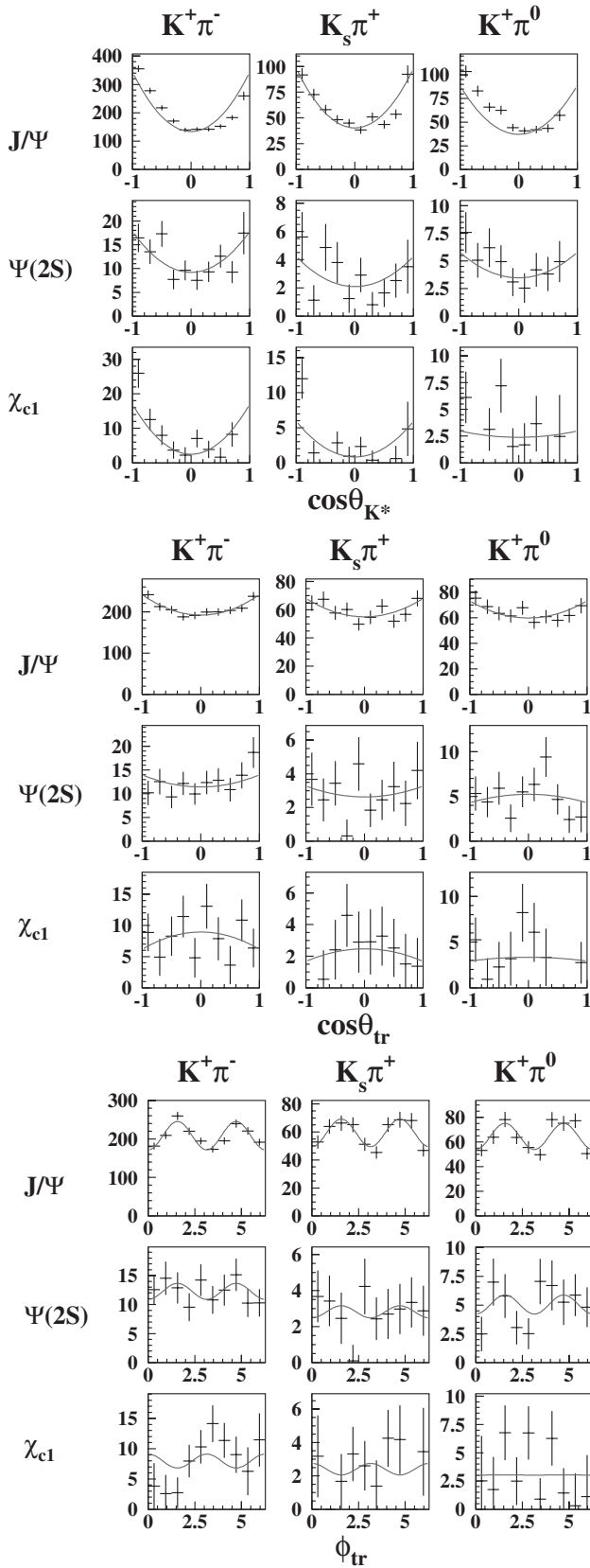


FIG. 2. Angular distributions with PDF from fit overlaid. The asymmetry of the $\cos\theta_{K^*}$ distributions induced by the S -wave interference is clearly visible.

ponent. The uncertainty due to the presence of a $K\pi S$ wave under the $K^*(892)$ peak is estimated by a fit including it. The differential decay rate is described by Eqs. (6–9) of Ref. [1].

The results are summarized in Table II. The values of $|A_0|^2$, $|A_{\parallel}|^2$, $|A_{\perp}|^2$ are negatively correlated due to the constraint $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$. In particular, $|A_{\parallel}|^2$, which would be the least precisely measured parameter in separate one-dimensional fits, is strongly anticorrelated with $|A_0|^2$, which would be the best measured. The one-dimensional (1D) distributions, acceptance-corrected with an 1D Ansatz and background-subtracted, are overlaid with the fit results and shown on Fig. 2. In contrast with the dedicated method used in the fit, for the plots, we simply computed the 1D efficiency maps from the distributions of the accepted events divided by the 1D PDF. As in lower statistics studies, the $\cos\theta_{K^*}$ forward-backward asymmetry due to the interference with the S wave is clearly visible.

Our measurement of the amplitudes of B decays to J/ψ are compatible with, and of better precision than, previous measurements. A comparison of neutral and charged B decays (not shown) yields results consistent with isospin symmetry. The strong phase difference $\delta_{\parallel} - \delta_{\perp}$ is obtained from a fit in which the phase origin is $\delta_{\perp} \equiv 0$. We confirm our previous observation that the strong phase differences are significantly different from zero, in contrast with what is predicted by factorization. For $B \rightarrow J/\psi K^*$, it amounts to $\delta_{\parallel} - \delta_{\perp} = 0.45 \pm 0.05 \pm 0.02$. The presence of direct CP -violating triple products in the amplitude would produce a B to \bar{B} difference in the interference terms \mathcal{A}_4 and \mathcal{A}_6 : $\delta\mathcal{A}_4$ and $\delta\mathcal{A}_6$. Our results (see Table III), with improved precision relative to Ref. [19], are consistent with no CP violation.

In summary, we have performed the first three-dimensional analysis of the decays to $\psi(2S)$ and χ_{c1} . The longitudinal polarization of the decay to $\psi(2S)$ is lower than that to J/ψ , while the CP -odd intensity fraction is higher (by 1.4 and 1.0 standard deviations, respectively). This is compatible with the prediction of models of meson decays in the framework of factorization. The longitudinal polarization of the decay to χ_{c1} is found to be larger than that to J/ψ , in contrast with the predictions of Ref. [8], which include nonfactorizable contributions. The CP -odd intensity fraction of this decay is compatible with zero. The parallel and longitudinal amplitudes for χ_{c1} seem to be aligned ($|\delta_{\parallel} - \delta_0| \sim 0$), while for ψ they are antialigned ($|\delta_{\parallel} - \delta_0| \sim \pi$).

TABLE III. Difference between the interference terms measured in B and \bar{B} decays to J/ψ .

	$\delta\mathcal{A}_4$	$\delta\mathcal{A}_6$
$(K^+ \pi^-)$	$0.002 \pm 0.025 \pm 0.005$	$-0.011 \pm 0.043 \pm 0.016$
$(K^+ \pi^0)$	$-0.017 \pm 0.047 \pm 0.023$	$-0.051 \pm 0.098 \pm 0.064$
$(K_S^0 \pi^+)$	$-0.008 \pm 0.049 \pm 0.011$	$0.075 \pm 0.089 \pm 0.009$

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