Measurement of the Decay Amplitudes of $B^0 \to J/\psi K^{*0}$ and $B_s{}^0 \to J/\psi \phi$ Decays

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(Received 12 July 2000)

An angular analysis of $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ has been used to determine the decay amplitudes with parity-even longitudinal (A_0) and transverse ($A_\parallel$) polarization and parity-odd transverse ($A_\perp$) polarization. The measurements are based on 190 B^0 and 40 B_s^0 candidates obtained from 89 pb^{-1} of $\bar{p}p$ collisions at the Fermilab Tevatron. The longitudinal decay amplitude dominates with $|A_0|^2 = 0.59 \pm 0.06 \pm 0.01$ for B^0 and $|A_0|^2 = 0.61 \pm 0.14 \pm 0.02$ for B_s^0 decays. The parity-odd amplitude is found to be small with $|A_\perp|^2 = 0.13^{+0.12}_{-0.09} \pm 0.06$ for B^0 and $|A_\perp|^2 = 0.23 \pm 0.19 \pm 0.04$ for B_s^0 decays.

PACS numbers: 13.25.Hw, 11.30.Er

The decays $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ are pseudoscalar to vector-vector decays and, in principle, have three decay amplitudes which can be determined by studying the angular distributions of the final state particles. These decays can have orbital angular momenta between the J/ψ and K^* (or ϕ) of 0, 1, or 2, and three decay amplitudes govern these transitions. Another convenient description is given in the transversity basis [1,2] in which the decay amplitudes are defined in terms of the linear polarization of the vector mesons. In this basis the $L = 1$ (P wave) decays are governed by a single decay amplitude, $A_\perp$, corresponding to a parity-odd correlation between transversely polarized vector mesons. The other two decay amplitudes, A_0 and $A_\parallel$, are combinations of the parity-even $L = 0$ and $L = 2$ (S and D wave) decays. The longitudinal polarization fraction, as is commonly defined in the helicity basis [3], is given by $\Gamma_L/\Gamma = |A_0|^2$.

Determination of the decay amplitudes and phases probes the limitations of the factorization hypothesis [4]. Factorization assumes that a weak decay matrix element can be described as the product of two independent (hadronic) currents, in this case treating the J/ψ and $B \to K^*$ (ϕ) as currents. To the extent that factorization holds, final state interactions are negligible. The matrix elements factorize into short and long distance (weak and strong) parts and the polarization decay amplitudes do not interfere and so are expected to be relatively real.

A measurement of the parity-odd amplitude, $A_\perp$, is pertinent to studies of CP invariance. For example, if the decay $B^0 \to J/\psi K^{*0}$ (with $K^{*0} \to K_s^0 \pi^0$) were to occur mainly through either a parity-odd or even amplitude, then this mode could be used [1,5] as readily as the $B^0 \to J/\psi K_s^0$ decay mode for determining [6] the CP nonconserving parameter $\sin(2\beta)$. The situation holds as well for the decay $B_s^0 \to J/\psi \phi$, which is expected to have a very small CP decay rate asymmetry in the standard Cabibbo-Kobayashi-Maskawa model. In addition the polarization of the decay $B_s^0 \to J/\psi \phi$ is interesting for its potential to improve the precision of measurements of the lifetime difference between the B_s^0 mass eigenstates via an angular analysis [2,7].

The longitudinal polarization in $B^0 \to J/\psi K^{*0}$ was first measured by ARGUS [8] as $\sim$1.0 followed by a CLEO [9] measurement of 0.8 ± 0.2 and a CDF (Collider Detector at Fermilab) measurement [10] of 0.65 ± 0.11. A full angular analysis by CLEO [11] obtained a longitudinal polarization fraction of 0.52 ± 0.08 and a parity-odd fraction of 0.16 ± 0.09. The only previous measurement of the B_s^0 decay mode, by CDF [10], obtained a longitudinal polarization fraction of 0.56 ± 0.21, consistent with the results for B^0, as expected under SU(3)-flavor symmetry.

This Letter describes a full angular analysis of both the B^0 and B_s^0 decay modes based on 89 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the CDF detector at the Fermilab Tevatron. In this analysis, the $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ decays are reconstructed from the decay modes $J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$, and $\phi \to K^+K^-$. After the selection described below, there are 190 $B^0 \to J/\psi K^{*0}$ and 40 $B_s^0 \to J/\psi \phi$ candidates above background. The results presented here are independent of those in Ref. [10].

CDF is a general purpose detector and has been described in detail elsewhere [12]. For this analysis important elements of the detector are the silicon vertex detector, with track impact parameter resolution of 10 μm, and the drift chamber, with charged particle momentum resolution of $\delta p_T/p_T \sim 0.001 p_T$, where P_T (in GeV/c) is the component of the momentum transverse to the $\bar{p}p$ collision axis. Chambers for muon detection provide coverage for particles with direction within 40° of the transverse direction.

The event sample for this measurement is selected by online trigger and offline reconstruction criteria. The trigger signature is the decay of a J/ψ to two muons. Hits in the muon chambers forming a track segment consistent with a nominal muon transverse momentum $P_T > 3.0$ GeV/c satisfy the first level of the trigger. Candidate muon track segments must be separated by more than 10° in the plane transverse to the collision axis. The second level requires drift chamber tracks, with $P_T > 2$ GeV/c, which extrapolate to the track segments in the muon chambers. The third level accepts J/ψ candidates with a reconstructed mass between 2.8 and 3.4 GeV/c^2.

The offline reconstruction first selects J/ψ candidates. Two muons of opposite charge satisfying quality requirements are combined into a J/ψ candidate. A kinematic fit requiring the muons to originate from a common vertex is performed, and the confidence level of the fit is required to be at least 0.01. This results in a sample of about 290 000 candidate J/ψ's.

Of these, candidates within 80 MeV/c^2 of the J/ψ mass (3096.88 MeV/c^2) [13] are then combined with two oppositely charged tracks that form a K^* (ϕ) for the $B^0 \to J/\psi K^{*0}$ ($B_s^0 \to J/\psi \phi$) decays. CDF lacks the particle identification capability to distinguish between the two

K-π charge assignments for a K^* candidate. However, the mass distribution for misidentified candidates is broader than the natural width of the K^* and their contribution is largely suppressed by choosing the assignment yielding a K^* mass closer to, and within 80 MeV/c^2 of, the world average (896.1 MeV/c^2).

To further improve the signal-to-noise ratio, the B^0 candidate is required to have $P_T > 6.0$ GeV/c, with the K^* having $P_T > 2.0$ GeV/c. All four particles from the B^0 decay are required to come from a common "secondary" vertex, with the confidence level of the fit being greater than 0.001. The proper decay length ($c \times$ proper decay time) for the B^0 is required to be at least 100 μm. The resulting $K\pi\mu^+\mu^-$ mass distribution is plotted in Fig. 1(a).

For the B_s^0 decay, the ϕ candidate is required to have a mass within 10 MeV/c^2 of the nominal ϕ mass (1019.4 MeV/c^2). The narrow natural width of the ϕ provides for better background rejection than the K^*. In order to compensate for the lower expected yield of B_s^0 events, looser requirements are imposed: transverse momentum cuts of 1.5 GeV/c and 4.5 GeV/c are applied to the ϕ and B_s^0 candidates. The confidence level of the four-track fit is again required to be greater than 0.001, and the proper decay length is required to be at least 50 μm. The resulting $KK\mu^+\mu^-$ mass distribution is plotted in Fig. 1(b).

The linear polarization of the vector mesons is determined from the angular distribution of the final state decay products. The decay angles are defined [2] as Θ_{K^*}, Θ_T, and Φ_T. In the rest frame of the K^*, Θ_{K^*} is the angle between the K momentum and the direction opposite the B meson (for the ϕ, the K^+ defines the angle). The transversity angles, Θ_T and Φ_T, are defined in the J/ψ rest frame: Θ_T is the angle between the μ^+ momentum and the perpendicular to the K^*-K plane; Φ_T is the azimuthal angle from the K^* to the projection of the μ^+ momentum onto the K^*-K plane.

The decay angular distribution is [7]:

$$\begin{aligned} d\Gamma/d\Omega \propto\ & 2\cos^2\Theta_{K^*}(1 - \sin^2\Theta_T\cos^2\Phi_T)\,|A_0|^2 + \sin^2\Theta_{K^*}(1 - \sin^2\Theta_T\sin^2\Phi_T)\,|A_\parallel|^2 + \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 \\ & + \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T\,\mathrm{Re}(A_0^*A_\parallel) \mp \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T\,\mathrm{Im}(A_\parallel^*A_\perp) \\ & \pm \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T\,\mathrm{Im}(A_0^*A_\perp)\,. \end{aligned}$$

Normalization of the distribution to unity implies $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$, and an unobservable phase is removed by requiring $\arg(A_0) = 0$. This leaves four measurable quantities: the polarization fractions, $\Gamma_L/\Gamma = |A_0|^2$ and $\Gamma_\perp/\Gamma = |A_\perp|^2$, and the phases of the matrix elements, $\arg(A_\parallel)$ and $\arg(A_\perp)$. CP invariance has been assumed throughout for the decay amplitudes.

The last two terms of the angular distribution have opposite signs for particle and antiparticle decay. The B^0 and $\overline{B}^0$ decays are flavor tagged by the charge of the K meson. The B_s^0 and $\overline{B}_s^0$ are not distinguishable by their final state particles, so for B_s^0 decays the information about the phase of $A_\perp$ is lost. The angular distribution as given holds initially, that is, at $t = 0$, for an untagged B_s sample. The time dependence of the terms will differ if the mass eigenstates have different lifetimes and in this case there can also be a CP violating contribution which is expected to be small (few percent) due to $B_s^0 - \overline{B}_s^0$ mixing in the standard model [7]. The small statistics of the B_s sample is such that the current measurement is not sensitive to a lifetime difference.

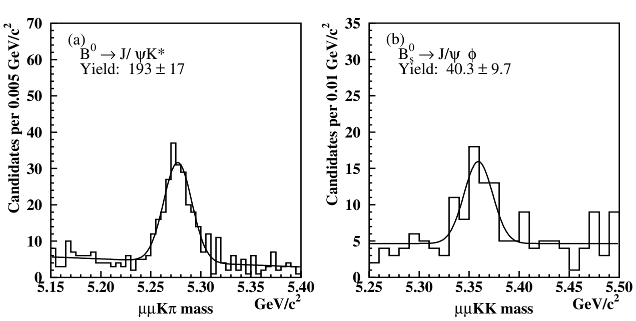

FIG. 1. Invariant mass distributions, after all selection requirements, for (a) $B^0 \to J/\psi K^{*0}$ and (b) $B_s^0 \to J/\psi\phi$ candidates.

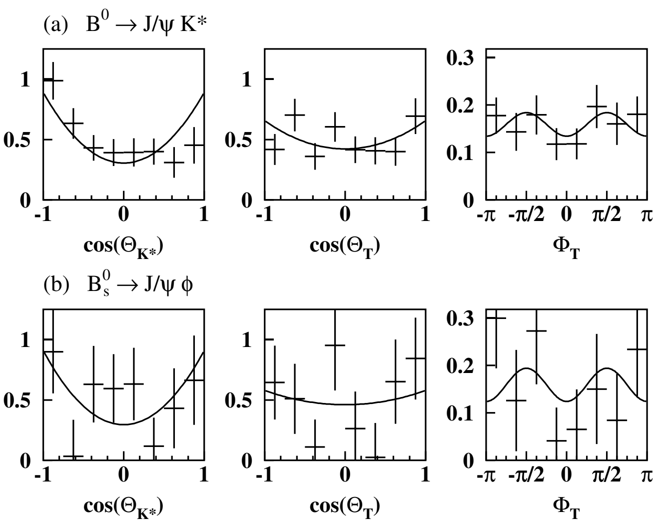

FIG. 2. Projections of the results from the full angular fit and the background subtracted data, corrected for acceptance, are shown for each of the decay angles, for (a) the $B^0 \to J/\psi K^{*0}$ mode and (b) the $B_s^0 \to J/\psi\phi$ mode.

TABLE I. Fitted decay amplitudes and phases (in radians). The uncertainties are statistical and systematic, respectively.

Quantity	$B^0 \to J/\psi K^{*0}$	$B_s^0 \to J/\psi \phi$
A_0	$0.77 \pm 0.04 \pm 0.01$	$0.78 \pm 0.09 \pm 0.01$
$A_\parallel$	$0.53 \pm 0.11 \pm 0.04$	$0.41 \pm 0.23 \pm 0.05$
$\arg(A_\parallel)$	$2.2 \pm 0.5 \pm 0.1$	$1.1 \pm 1.3 \pm 0.2$
$A_\perp$	$0.36 \pm 0.16 \pm 0.08$	$0.48 \pm 0.20 \pm 0.04$
$\arg(A_\perp)$	$-0.6 \pm 0.5 \pm 0.1$	$\cdots$
$\Gamma_L/\Gamma = \lvert A_0\rvert^2$	$0.59 \pm 0.06 \pm 0.01$	$0.61 \pm 0.14 \pm 0.02$
$\Gamma_\perp/\Gamma = \lvert A_\perp\rvert^2$	$0.13\,^{+0.12}_{-0.09} \pm 0.06$	$0.23 \pm 0.19 \pm 0.04$

The matrix elements are extracted by fitting the observed decay angular distribution. The fit is performed over the decay angles and the B candidate mass range covered in Fig. 1. To account for detector acceptance and selection criteria, Monte Carlo events are generated with detector and trigger simulations and processed by the same reconstruction software used on the data. The fit method uses an unbinned log-likelihood with the normalization depending on the parameters in the fit [14,15].

The background is modeled by a sum of polynomial terms of $\cos\Theta_{K^*}$ and $\cos\Theta_T$, and sines and cosines of Φ_T and $2\Phi_T$. The background angular distribution is determined from the events on both sides of the B meson mass peak.

Additional terms are included in the angular distribution to account for the residual probability ($\sim$6%) of misidentifying the final state hadrons in the selected $B^0 \to J/\psi K^{*0}$ decays. Events reconstructed under the wrong hypothesis will yield incorrect decay angles having a distribution different from, but fully correlated with, the polarized decay distribution. The augmented likelihood function corrects for the effect based on the kinematics as determined from Monte Carlo.

The results from the global fit are illustrated in Fig. 2. The independent variables are functions of the transversity angles: $\cos\Theta_{K^*}$, $\cos\Theta_T$, and Φ_T. The points are the background subtracted projection of the data corrected for detector and reconstruction efficiencies. The superimposed curves are derived from the results of the global fit.

Sources of systematic uncertainty are, in order of importance, the model of the background shape, Monte Carlo B generation parameters, trigger simulation, and B^0-B_s^0 cross talk. The last two are found to have negligible contribution. The uncertainty of the final result is still dominated by the statistics of the event sample [14].

The underlying background shape is not known from first principles. To estimate the systematic uncertainty from the background modeling, multiple fits with different parametrizations of the background decay angles were studied. Different models of the shape are sensitive to different inaccuracies of the background shape function, and the spread in the fitted values is used to estimate the sensitivity to possibly unaccounted structure.

The input parameters to the Monte Carlo generation of B mesons are the b quark mass and generation mass scales, the parton distribution functions, and fragmentation parameters. The effect on the measurement is determined by varying the parameters by their nominal uncertainties and refitting for the decay amplitudes. Systematic uncertainties due to the modeling of the trigger selection criteria are studied in a similar fashion.

The similarity of the decay kinematics for the B^0 and B_s^0 decays allows for a possible cross contamination through K-π misidentification. Monte Carlo studies give contamination fractions of 2.1% (4.4%) in the B^0 (B_s^0) sample. The assigned systematic uncertainty is equal to the difference in the B^0 and B_s^0 polarization fraction, multiplied by the contamination fraction.

The final results of this analysis are summarized in Table I, and are illustrated in Fig. 3. For the $B^0 \to J/\psi K^{*0}$ the magnitudes of decay amplitudes are in good agreement with the results from CLEO [11]. The longitudinal polarization fraction dominates: $\Gamma_L/\Gamma = |A_0|^2 = 0.59 \pm 0.06 \pm 0.01$ and the parity-odd fraction is small: $\Gamma_\perp/\Gamma = |A_\perp|^2 = 0.13^{+0.12}_{-0.09} \pm 0.06$. In contrast to the CLEO result, the CDF measurement for the phase of $A_\parallel$ favors the presence of strong final state interactions, inasmuch as $\arg(A_\parallel)$ is not close to 0 or π. However, the results from the two experiments are not inconsistent, given their uncertainties. The results for the $B_s^0 \to J/\psi \phi$

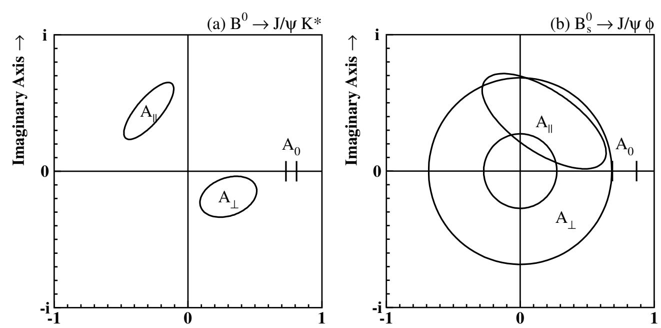

FIG. 3. One-standard-deviation contours, including statistical and systematic uncertainties, for the fitted decay amplitudes in the complex plane, for (a) $B^0 \to J/\psi K^{*0}$ and (b) $B_s^0 \to J/\psi \phi$ decays.

are the first available from a full angular analysis. The B_s^0 results also show a dominant longitudinal polarization fraction $\Gamma_L/\Gamma = |A_0|^2 = 0.61 \pm 0.14 \pm 0.02$ and a small parity-odd fraction: $\Gamma_\perp/\Gamma = |A_\perp|^2 = 0.23 \pm 0.19 \pm 0.04$, consistent with the B^0 results and SU(3) flavor symmetry.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This research was supported by the U.S. Department of Energy and the National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; and the Bundesministerium für Bildung und Forschung, Germany. We thank H. Lipkin for bringing the transversity basis to our attention and acknowledge illuminating correspondence and discussions with I. Dunietz and J. Rosner.

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