Measurement of the Decay Amplitudes and Branching Fractions of $B \to J/\psi K^*$ and $B \to J/\psi K$ Decays

C. P. Jessop,[1] K. Lingel,[1] H. Marsiske,[1] M. L. Perl,[1] S. F. Schaffner,[1] D. Ugolini,[1] R. Wang,[1] X. Zhou,[1] T. E. Coan,[2] V. Fadeyev,[2] I. Korolkov,[2] Y. Maravin,[2] I. Narsky,[2] V. Shelkov,[2] J. Staeck,[2] R. Stroynowski,[2] I. Volobouev,[2] J. Ye,[2] M. Artuso,[3] A. Efimov,[3] F. Frasconi,[3] M. Gao,[3] M. Goldberg,[3] D. He,[3] S. Kopp,[3] G. C. Moneti,[3] R. Mountain,[3] Y. Mukhin,[3] S. Schuh,[3] T. Skwarnicki,[3] S. Stone,[3] G. Viehhauser,[3] X. Xing,[3] J. Bartelt,[4] S. E. Csorna,[4] V. Jain,[4] S. Marka,[4] A. Freyberger,[5] R. Godang,[5] K. Kinoshita,[5] I. C. Lai,[5] P. Pomianowski,[5] S. Schrenk,[5] G. Bonvicini,[6] D. Cinabro,[6] R. Greene,[6] L. P. Perera,[6] B. Barish,[7] M. Chadha,[7] S. Chan,[7] G. Eigen,[7] J. S. Miller,[7] C. O'Grady,[7] M. Schmidtler,[7] J. Urheim,[7] A. J. Weinstein,[7] F. Würthwein,[7] D. M. Asner,[8] D. W. Bliss,[8] W. S. Brower,[8] G. Masek,[8] H. P. Paar,[8] V. Sharma,[8] J. Gronberg,[9] R. Kutschke,[9] D. J. Lange,[9] S. Menary,[9] R. J. Morrison,[9] H. N. Nelson,[9] T. K. Nelson,[9] C. Qiao,[9] J. D. Richman,[9] D. Roberts,[9] A. Ryd,[9] M. S. Witherell,[9] R. Balest,[10] B. H. Behrens,[10] K. Cho,[10] W. T. Ford,[10] H. Park,[10] P. Rankin,[10] J. Roy,[10] J. G. Smith,[10] J. P. Alexander,[11] C. Bebek,[11] B. E. Berger,[11] K. Berkelman,[11] K. Bloom,[11] D. G. Cassel,[11] H. A. Cho,[11] D. M. Coffman,[11] D. S. Crowcroft,[11] M. Dickson,[11] P. S. Drell,[11] K. M. Ecklund,[11] R. Ehrlich,[11] R. Elia,[11] A. D. Foland,[11] P. Gaidarev,[11] B. Gittelman,[11] S. W. Gray,[11] D. L. Hartill,[11] B. K. Heltsley,[11] P. I. Hopman,[11] J. Kandaswamy,[11] N. Katayama,[11] P. C. Kim,[11] D. L. Kreinick,[11] T. Lee,[11] Y. Liu,[11] G. S. Ludwig,[11] J. Masui,[11] J. Mevissen,[11] N. B. Mistry,[11] C. R. Ng,[11] E. Nordberg,[11] M. Ogg,[11,*] J. R. Patterson,[11] D. Peterson,[11] D. Riley,[11] A. Soffer,[11] C. Ward,[11] M. Athanas,[12] P. Avery,[12] C. D. Jones,[12] M. Lohner,[12] C. Prescott,[12] S. Yang,[12] J. Yelton,[12] J. Zheng,[12] G. Brandenburg,[13] R. A. Briere,[13] Y. S. Gao,[13] D. Y.-J. Kim,[13] R. Wilson,[13] H. Yamamoto,[13] T. E. Browder,[14] F. Li,[14] Y. Li,[14] J. L. Rodriguez,[14] T. Bergfeld,[15] B. I. Eisenstein,[15] J. Ernst,[15] G. E. Gladding,[15] G. D. Gollin,[15] R. M. Hans,[15] E. Johnson,[15] I. Karliner,[15] M. A. Marsh,[15] M. Palmer,[15] M. Selen,[15] J. J. Thaler,[15] K. W. Edwards,[16] A. Bellerive,[17] R. Janicek,[17] D. B. MacFarlane,[17] K. W. McLean,[17] P. M. Patel,[17] A. J. Sadoff,[18] R. Ammar,[19] P. Baringer,[19] A. Bean,[19] D. Besson,[19] D. Coppage,[19] C. Darling,[19] R. Davis,[19] N. Hancock,[19] S. Kotov,[19] I. Kravchenko,[19] N. Kwak,[19] S. Anderson,[20] Y. Kubota,[20] M. Lattery,[20] J. J. O'Neill,[20] S. Patton,[20] R. Poling,[20] T. Riehle,[20] V. Savinov,[20] A. Smith,[20] M. S. Alam,[21] S. B. Athar,[21] Z. Ling,[21] A. H. Mahmood,[21] H. Severini,[21] S. Timm,[21] F. Wappler,[21] A. Anastassov,[22] S. Blinov,[22,†] J. E. Duboscq,[22] K. D. Fisher,[22] D. Fujino,[22,‡] R. Fulton,[22] K. K. Gan,[22] T. Hart,[22] K. Honscheid,[22] H. Kagan,[22] R. Kass,[22] J. Lee,[22] M. B. Spencer,[22] M. Sung,[22] A. Undrus,[22,†] R. Wanke,[22] A. Wolf,[22] M. M. Zoeller,[22] B. Nemati,[23] S. J. Richichi,[23] W. R. Ross,[23] P. Skubic,[23] M. Wood,[23] M. Bishai,[24] J. Fast,[24] E. Gerndt,[24] J. W. Hinson,[24] N. Menon,[24] D. H. Miller,[24] E. I. Shibata,[24] I. P. J. Shipsey,[24] M. Yurko,[24] L. Gibbons,[25] S. D. Johnson,[25] Y. Kwon,[25] S. Roberts,[25] and E. H. Thorndike[25]

(CLEO Collaboration)

[1]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[2]*Southern Methodist University, Dallas, Texas 75275*
[3]*Syracuse University, Syracuse, New York 13244*
[4]*Vanderbilt University, Nashville, Tennessee 37235*
[5]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[6]*Wayne State University, Detroit, Michigan 48202*
[7]*California Institute of Technology, Pasadena, California 91125*
[8]*University of California, San Diego, La Jolla, California 92093*
[9]*University of California, Santa Barbara, California 93106*
[10]*University of Colorado, Boulder, Colorado 80309-0390*
[11]*Cornell University, Ithaca, New York 14853*
[12]*University of Florida, Gainesville, Florida 32611*
[13]*Harvard University, Cambridge, Massachusetts 02138*
[14]*University of Hawaii at Manoa, Honolulu, Hawaii 96822*
[15]*University of Illinois, Champaign-Urbana, Illinois 61801*
[16]*Carleton University, Ottawa, Ontario, Canada K1S 5B6, and the Institute of Particle Physics, Canada*
[17]*McGill University, Montréal, Québec, Canada H3A 2T8, and the Institute of Particle Physics, Canada*
[18]*Ithaca College, Ithaca, New York 14850*
[19]*University of Kansas, Lawrence, Kansas 66045*
[20]*University of Minnesota, Minneapolis, Minnesota 55455*

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[21]State University of New York at Albany, Albany, New York 12222
[22]The Ohio State University, Columbus, Ohio 43210
[23]University of Oklahoma, Norman, Oklahoma 73019
[24]Purdue University, West Lafayette, Indiana 47907
[25]University of Rochester, Rochester, New York 14627
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Using data taken with the CLEO II detector at the Cornell Electron Storage Ring, we present the first full angular analysis in the color-suppressed modes $B^0 \to J/\psi\, K^{*0}$ and $B^+ \to J/\psi\, K^{*+}$. This leads to a complete determination of the decay amplitudes of these modes including the longitudinal polarization $\Gamma_L/\Gamma = 0.52 \pm 0.07 \pm 0.04$ and the P wave component $|P|^2 = 0.16 \pm 0.08 \pm 0.04$. In addition, we update the branching fractions for $B \to J/\psi\, K$ and $B \to J/\psi\, K^*$. [S0031-9007(97)04447-5]

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One of the interests in $B \to J/\psi\, K^*$ decays is their role in CP violation measurements at asymmetric B-factories. The vector-vector decay $B^0 \to J/\psi\, K^{*0}$, with $K^{*0} \to K_S^0 \pi^0$, is a mixture of CP-even and CP-odd eigenstates since it can proceed via an S, P, or D wave decay. If one CP eigenstate dominates or if the two CP eigenstates can be separated, this decay can be used to measure the angle β of the unitarity triangle in a manner similar to which the CP-odd eigenstate $B^0 \to J/\psi\, K_S^0$ is used. Therefore the determination of the P wave component in $B \to J/\psi\, K^*$ decays is of great interest for future CP violation measurements.

Measurements of the decay amplitudes of $B \to J/\psi\, K^{(*)}$ transitions also provide a test of the factorization hypothesis in decays with internal W emission. Several phenomenological models, based on the factorization hypothesis, predict the longitudinal polarization fraction in $B \to J/\psi\, K^*$, denoted Γ_L/Γ, and the ratio of vector to pseudoscalar meson production, $R \equiv \mathcal{B}(B \to J/\psi\, K^*)/\mathcal{B}(B \to J/\psi\, K)$ [1–5]. It has been noted [5,6] that form factor models cannot simultaneously explain the earlier experimental data for these two quantities. The high values of $\Gamma_L/\Gamma = 0.97 \pm 0.16 \pm 0.15$ measured by ARGUS [7] and $\Gamma_L/\Gamma = 0.80 \pm 0.08 \pm 0.05$ measured by CLEO II [8], with low statistics, are not consistent with factorization and the measured value of R. The CDF Collaboration has measured a lower value of $\Gamma_L/\Gamma = 0.65 \pm 0.10 \pm 0.04$ [9]. Additional information about the validity of factorization can be obtained by a measurement of the decay amplitude phases, since any nontrivial phase differences indicate final state interactions and the breakdown of factorization [10].

In this paper we present a complete angular analysis and an update of the branching fractions for $B \to J/\psi\, K^{(*)}$ decays using the full CLEO II data sample. Assuming isospin symmetry, we determine the fraction of longitudinal polarization, the parity content, and the phase differences of the decay amplitudes from the modes $B^+ \to J/\psi\, K^{*+}$ and $B^0 \to J/\psi\, K^{*0}$ using the K^{*+} and K^{*0} decay modes to $K^+\pi^0$, $K^0\pi^+$, $K^+\pi^-$, and $K^0\pi^0$. The J/ψ is reconstructed in its leptonic decay modes to e^+e^- and $\mu^+\mu^-$. The measurements presented here supersede previous CLEO II results [8], which are based on a subset of the data used for this analysis.

The decay $B \to J/\psi\, K^*$ is described by three complex decay amplitudes. Following a suggestion of Dunietz *et al.* [11,12], we measure the decay amplitudes $A_0 = -\sqrt{1/3}\,S + \sqrt{2/3}\,D$, $A_\parallel = \sqrt{2/3}\,S + \sqrt{1/3}\,D$, and $A_\perp = P$, where S, P, and D denote S, P, and D wave amplitudes, respectively. Normalizing the decay amplitudes to $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$ and eliminating one overall phase leaves four independent parameters.

The full angular distribution of a B meson decaying into two vector particles is specified by three angles. Previously the helicity angle basis [13] has been used for angular analyses of $B \to J/\psi\, K^*$ decays. Because of its convenience for extracting the parity information, we use a different set of angles, called the transversity basis [12]. The direction of the K^* in the J/ψ rest frame defines the x axis of a right-handed coordinate system. The $K\pi$ plane fixes the y axis with $p_y(K) > 0$ and the normal to this plane defines the z axis. The transversity angles $\theta_{\rm tr}$ and $\phi_{\rm tr}$ are then defined as polar and azimuth angles of the l^+ in the J/ψ rest frame. The third angle, the K^* decay angle θ_{K^*}, is defined as that of the K in the K^* rest frame relative to the negative of the J/ψ direction in that frame. Using these definitions the full angular distribution of the $B \to J/\psi\, K^*$ decay is [12]

$$\begin{aligned}\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_{\rm tr}\,d\cos\theta_{K^*}\,d\phi_{\rm tr}} = \frac{9}{32\pi}\{&2|A_0|^2\cos^2\theta_{K^*}(1-\sin^2\theta_{\rm tr}\cos^2\phi_{\rm tr}) + |A_\parallel|^2\sin^2\theta_{K^*}(1-\sin^2\theta_{\rm tr}\sin^2\phi_{\rm tr}) \\ &+ |A_\perp|^2\sin^2\theta_{K^*}\sin^2\theta_{\rm tr}\sin^2\phi_{\rm tr} - \mathrm{Im}(A_\parallel^* A_\perp)\sin^2\theta_{K^*}\sin 2\theta_{\rm tr}\sin\phi_{\rm tr} \\ &+ \frac{1}{\sqrt{2}}\mathrm{Re}(A_0^* A_\parallel)\sin 2\theta_{K^*}\sin^2\theta_{\rm tr}\sin 2\phi_{\rm tr} + \frac{1}{\sqrt{2}}\mathrm{Im}(A_0^* A_\perp)\sin 2\theta_{K^*}\sin 2\theta_{\rm tr}\cos\phi_{\rm tr}\}\,.\end{aligned}$$

For $\overline{B}$ decays the interference terms containing $A_\perp$ switch sign while all other terms remain unchanged.

The data for this analysis were recorded with the CLEO II detector located at the Cornell Electron Storage Ring

(CESR). We have used a data sample of approximately 3.4×10^6 $B\overline{B}$ events taken on the $\Upsilon(4S)$ resonance and representing an integrated luminosity of 3.1 fb^{-1}. To evaluate non-$b\overline{b}$ backgrounds, we have collected a "continuum" data sample 60 MeV below the $\Upsilon(4S)$ resonance, with an integrated luminosity of about 1.6 fb^{-1}.

The components of the CLEO II detector [14] most relevant to this analysis are the charged particle tracking, the CsI electromagnetic calorimeter, and the muon counters. The tracking system comprises a set of precision drift chambers totaling 67 layers inside a 1.5 T solenoidal magnet. It measures both momentum and specific ionization (dE/dx) of charged particles.

Electron candidates are identified by their energy deposition in the calorimeter, which must equal their measured momenta, and their specific ionization, which must be consistent with that expected for electrons. At least one muon candidate is required to have penetrated five nuclear interaction lengths of material while the other must have penetrated at least three interaction lengths. The decays $B^+ \to J/\psi\, K^+$ and $B^0 \to J/\psi\, K_S^0$ have little background; therefore only one of the two leptons has to be positively identified. We require the dimuon invariant mass to be within 45 MeV$/c^2$ of the J/ψ mass, which corresponds to a 3σ selection. For the dielectron invariant mass we require $-150 < m_{ee} - m_{J/\psi} < 45$ MeV$/c^2$ to allow for the radiative tail. The J/ψ energy resolution is improved by a factor of 5–6 by performing a kinematic fit of the dilepton mass to the nominal J/ψ mass. The angle measurements are not affected by the kinematic fit. Their resolution is better than 0.06 radian for all decay angles.

We require the charged hadron candidates to have dE/dx measurements that lie within 3 standard deviations of the expected values. We reconstruct K_S^0 candidates through the decay to $\pi^+\pi^-$ and π^0 candidates through the decay to $\gamma\gamma$. Candidate K^* mesons are required to have a $K\pi$ invariant mass within 75 MeV$/c^2$ of the nominal K^* mass.

In symmetric e^+e^- annihilations at the $\Upsilon(4S)$ resonance, the energy of a B meson must equal the beam energy. We require the energy difference $|\Delta E|$ between the B candidate and the beam energy to be less than 45 MeV for $J/\psi\, K^+$ and $J/\psi\, K_S^0$, less than 30 MeV for $J/\psi(K^+\pi^-)$ and $J/\psi(K_S^0\pi^+)$, and less than 60 MeV for $J/\psi(K^+\pi^0)$ and $J/\psi(K_S^0\pi^0)$. These ranges correspond to approximately 3σ in $|\Delta E|$. Since the resolution on the beam energy is an order of magnitude better than the resolution on the B candidate energy, we substitute the beam energy in the calculation of the B-candidate mass (referred to as the "beam-constrained mass" m_B). The detection efficiencies range from 48% for the $B^+ \to J/\psi\, K^+$ mode down to 9% for $B^0 \to J/\psi\, K^{*0}$ with $K^{*0} \to K_S^0\pi^0$.

The most severe background in the $B \to J/\psi\, K^*$ modes are misidentified decays of another $B \to J/\psi\, K^*$ mode. For such events both the total energy and the beam-constrained mass are very close to the signal region. The biggest source of this background is from swapping a random or misidentified slow π^0 for the correct one. Consequently most background events have the π^0 moving backwards with respect to the K^* direction of flight. To suppress this background we require the K^* decay angle to satisfy $\cos\theta_{K^*} < 0.7$ in these decays. This is equivalent to a constraint on the π^0 momentum, corresponding to a minimum p_{π^0} of about 200 MeV$/c$. The total fraction of misidentified $B \to J/\psi\, K^*$ events in the signal region, averaged over all K^* modes, is 8.0%.

Examining the $K\pi$ invariant mass spectrum (Fig. 1) shows an excess of events between 1.1 and 1.45 GeV$/c^2$. By computing the kinematics of nonresonant $B \to J/\psi\, X_s$ decays, using both the J/ψ momentum spectrum from inclusive B decays [15] and several theoretical models [16], we do expect strangeness-containing final states with invariant masses in this region. Decays via higher K^* resonances may have line shapes consistent with the $m_{K\pi}$ distribution seen by us [17]. Unfortunately, due to the limited statistics for $m_{K\pi} > 1.1$ GeV$/c^2$, we cannot distinguish between possible components. By extrapolation of the sideband, we estimate the amount of the non-$K^*(892)$ contribution in the signal region to be 6.4% with a conservatively chosen systematic uncertainty of $\pm 100\%$. In addition, we considered many other possible origins for the excess events above 1.1 GeV$/c^2$, including misidentified events from other $B \to J/\psi\, X$ modes such as $B \to J/\psi\, K^*\pi$, $B \to J/\psi\, K\rho$, or $B \to J/\psi\, K$, and found none of these to contribute significantly.

With a similar analysis CLEO has found nine events for $B^0 \to J/\psi\, \rho^0$ [18]. If a pion from the ρ^0 is misidentified as a kaon, $m_{K\pi}$ could fall in the K^* region but these events would fail the $|\Delta E|$ energy criterion. For the same reason other misidentified $B \to J/\psi\, X$ decays, like $B \to J/\psi\, K^*\pi$ or misidentifications between the $J/\psi\, K$ and $J/\psi\, K^*$ modes, do not contribute significantly to the

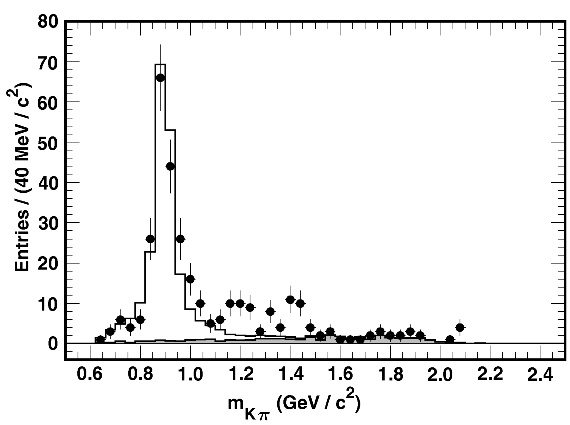

FIG. 1. The $m_{K\pi}$ distribution for $m_B > 5.27$ GeV$/c^2$. Shown are the data points, the fitted $K^*(892)$ mass peak including background from misidentified $B \to J/\psi\, K^*$ decays (histogram), and the combinatorial background (shaded).

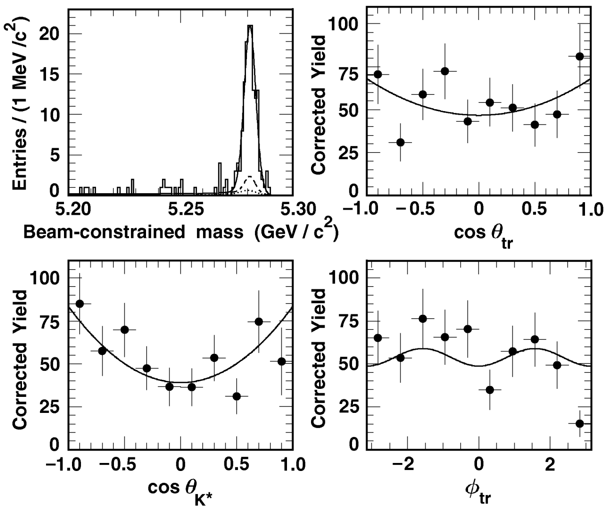

FIG. 2. Projections of the four-dimensional fit to the $B \to J/\psi K^*$ data. The plot of the beam-constrained mass shows the data (histogram), the fit (solid line), the sum of all backgrounds (dashed), and the contribution of misidentified $B \to J/\psi K^*$ events (dotted). The angular distributions are background subtracted and efficiency corrected.

background since they lie outside the energy window. Furthermore, the contributions are uniform in the beam-constrained mass.

We define combinatorial backgrounds to be events that do not contain a true $J/\psi \to l^+ l^-$ decay. In both the $B\overline{B}$ Monte Carlo simulation and our continuum data sample we see very few such events.

We must correct our data for detection efficiency. To obtain the efficiency as a function of all three angles, a large Monte Carlo sample (120 000 events/K^* mode) is divided into a $20 \times 20 \times 10$ grid in $\cos\theta_{\rm tr}$, $\cos\theta_{K^*}$, and $\phi_{\rm tr}$. For each $J/\psi K^*$ final state the efficiency is fitted separately with polynomials in three dimensions including all correlations. The efficiency distributions are nearly uniform in all angles except the K^* decay angle, where it drops at high $\cos\theta_{K^*}$ because of the slow pion.

To determine the decay amplitudes, a four-dimensional unbinned maximum likelihood fit is performed to the distributions of the three angles and the beam-constrained mass. Setting $\phi(A_0) \equiv 0$, we fit for the longitudinal polarization fraction, $|A_0|^2 = \Gamma_L/\Gamma$, the parity-odd fraction, $|A_\perp|^2 = |P|^2$, and the phases $\phi(A_\parallel)$ and $\phi(A_\perp)$. Other free parameters in the fit are the branching fraction $\mathcal{B}(B \to J/\psi K^*)$, the mean of the m_B distribution, and the normalization of the combinatorial background of each mode. The simultaneous fitting for the branching fraction and the polarization parameters ensures both the statistically correct treatment of the background events and the adjustment of the branching fraction measurement for the polarization dependence of the efficiency. The one-dimensional projections of the resulting fit function are shown in Fig. 2. The results are listed in Table I. The correlations between the fit parameters are small. Note that for polarization parameters, like Γ_L/Γ and $|P|^2$, the statistical errors depend on the fitted mean values, which explains the relatively small statistical error of Γ_L/Γ in the previous ARGUS and CLEO II measurements compared to this measurement. The systematic uncertainties of the decay amplitude measurements are dominated by those in the efficiency parametrization and background polarization and are small compared to the statistical errors.

TABLE I. Resulting decay amplitudes from the fit to the transversity angles. The phase $\phi(A_0)$ has been set to zero. The first error is statistical and the second is the estimated systematic uncertainty.

Parameter	Value
$\|A_0\|^2 = \Gamma_L/\Gamma$	$0.52 \pm 0.07 \pm 0.04$
$\|A_\perp\|^2 = \|P\|^2$	$0.16 \pm 0.08 \pm 0.04$
$\phi(A_\perp)$	$-0.11 \pm 0.46 \pm 0.03$ rad
$\phi(A_\parallel)$	$3.00 \pm 0.37 \pm 0.04$ rad

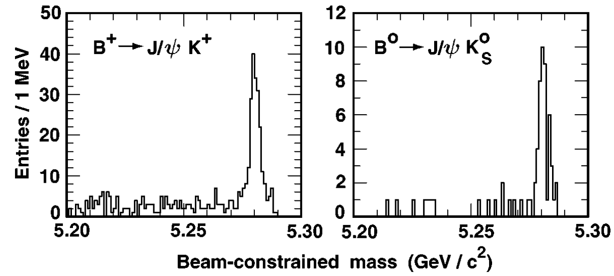

FIG. 3. Beam-constrained mass distributions for the decays $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^0$.

We repeated the fit to the decay amplitudes using helicity angles rather than transversity angles as well as performing one-dimensional fits to both the longitudinal polarization fraction and the parity-odd component. An independent angular analysis with the same data sample has also been performed, using a Monte Carlo technique [19] to evaluate the likelihood function. All results are in agreement with those reported here.

These results are the first determination of the parity-odd component and the phases of the decay amplitudes of the $B \to J/\psi K^*$ decay. The small fraction of the parity-odd component encourages using the $B^0 \to J/\psi K_S^0 \pi^0$ decay for CP violation studies at asymmetric B-factories. The phases of the decay amplitudes are measured to be

TABLE II. Measured signal yields and branching fractions.

Decay mode	Signal yield	Branching fraction $[10^{-3}]$
$B^+ \to J/\psi K^+$	198.1 ± 14.9	$1.02 \pm 0.08 \pm 0.07$
$B^0 \to J/\psi K^0$	$45.5^{+7.3}_{-6.6}$	$0.85^{+0.14}_{-0.12} \pm 0.06$
$B^+ \to J/\psi K^{*+}$	42.5 ± 7.1	$1.41 \pm 0.23 \pm 0.24$
$B^0 \to J/\psi K^{*0}$	81.6 ± 10.3	$1.32 \pm 0.17 \pm 0.17$

TABLE III. Comparison between this measurement and model predictions for Γ_L/Γ and the ratio R.

Model	Γ_L/Γ	R
Neubert *et al.* [3]	0.35	1.61
Deandrea *et al.* [4,6]	0.36	1.50
Aleksan *et al.* [5]	0.45	2.15
This measurement	$0.52 \pm 0.07 \pm 0.04$	$1.45 \pm 0.20 \pm 0.17$

close to zero or π, giving no evidence for strong final state interactions.

The branching fractions of the $B \to J/\psi K^*$ decays are a result of the angular fit. To measure the $B \to J/\psi K^+/K^0$ branching fractions we performed one-dimensional fits to the beam-constrained mass distributions shown in Fig. 3. All measured branching fractions are listed in Table II, where we have assumed that the production rate of neutral and charged B mesons is the same on the $\Upsilon(4S)$ resonance, in agreement with the actual measured value of $f_{+-}/f_{00} = 1.12 \pm 0.20$ [20] and a theoretical prediction [21]. The main sources of systematic uncertainties of the $B \to J/\psi K$ branching fraction measurements are track finding, track fitting, lepton identification efficiencies, and the uncertainty of the world average of $\mathcal{B}(J/\psi \to l^+l^-)$ [22]. In the $B \to J/\psi K^*$ branching ratios, uncertainties in the amount of misidentified $B \to J/\psi K^*$ decays and non-K^* decays dominate the systematic error.

With the assumption of equal partial widths, $\Gamma(B^+ \to J/\psi K^{(*)+}) = \Gamma(B^0 \to J/\psi K^{(*)0})$, and eliminating common systematic uncertainties we determine $(f_{+-}/f_{00}) \times (\tau_{B^+}/\tau_{B^0}) = 1.15 \pm 0.17 \pm 0.06$.

Assuming isospin invariance, we find for the ratio of pseudoscalar to vector meson production $R = \mathcal{B}(B \to J/\psi K^*)/\mathcal{B}(B \to J/\psi K) = 1.45 \pm 0.20 \pm 0.17$.

Table III compares these measurements of Γ_L/Γ and the ratio R with recent theoretical predictions using the factorization approach, indicating that the discrepancy with naive factorization models is not as acute as before.

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*Permanent address: University of Texas, Austin, TX 78712.

†Permanent address: BINP, RU-630090 Novosibirsk, Russia.

‡Permanent address: Lawrence Livermore National Laboratory, Livermore, CA 94551.

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