Reconstruction of $B^0 \to J/\psi\, K_S^0$ and Measurement of Ratios of Branching Ratios Involving $B \to J/\psi\, K^*$ and $B^+ \to J/\psi\, K^+$

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We report on the reconstruction of the decay mode $B^0 \to J/\psi\, K_S^0$ using 19.3 pb^{-1} of data collected by the Collider Detector at Fermilab in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. A signal of 41.8 ± 6.9 events, with a signal-to-background ratio of 9:1, is observed. Three additional decay modes $B^+ \to J/\psi\, K^+$, $B^0 \to J/\psi\, K^*(892)^0$, and $B^+ \to J/\psi\, K^*(892)^+$ are reconstructed. We measure three ratios of branching ratios, each one relative to the $B^+ \to J/\psi\, K^+$ mode. We also report the ratio of decay rates, $\Gamma(B \to J/\psi\, K^*)/\Gamma(B \to J/\psi\, K)$, for the vector-vector relative to the vector-pseudoscalar modes, to be $1.32 \pm 0.23(\text{stat}) \pm 0.16(\text{syst})$.

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This Letter reports on the reconstruction of the decay $B^0 \to J/\psi\, K_S^0$ [1] with the subsequent decay $K_S^0 \to \pi^+\pi^-$ and on three additional $B \to J/\psi\, K^*$ modes [2]. We reconstruct the isospin partner $B^+ \to J/\psi\, K^+$ and the pseudoscalar-to-vector-vector transitions, $B^0 \to J/\psi\, K^*(892)^0$ and $B^+ \to J/\psi\, K^*(892)^+$. We measure three ratios of branching ratios, $B(B^0 \to J/\psi\, K^0)/B(B^+ \to J/\psi\, K^+)$, $B(B^0 \to J/\psi\, K^*(892)^0)/B(B^+ \to J/\psi\, K^+)$, $B(B^+ \to J/\psi\, K^*(892)^+)/B(B^+ \to J/\psi\, K^+)$, and report the ratio formed by combining the pseudoscalar-to-vector-vector modes relative to the pseudoscalar-to-vector-pseudoscalar modes, which we refer to as the "vector-pseudoscalar ratio." By forming ratios, we minimize several systematic uncertainties, the largest of which are associated with the b-quark production cross section and transverse momentum spectrum. Together with information on the polarization in the decay $B \to J/\psi K^*$ [3–5], these decay modes are of particular interest to test theoretical predictions that depend on the factorization hypothesis [6,7] and the $B \to K^*$ form factor [8].

The decay mode $B^0 \to J/\psi K_S^0$ is expected to provide the first observation of CP violation outside the kaon system. From a theoretical point of view, the decay $B^0 \to J/\psi K_S^0$ has several properties that make it ideal for the search for CP violation in the b-quark system [9,10]. Experimentally, a large cross section for B meson production at the Fermilab Tevatron collider has been measured [11]. Furthermore, the decay of the $J/\psi \to \mu^+\mu^-$ simplifies the triggering and the long lifetime of the K_S^0 permits the isolation of a clean K_S^0 signal in the hadron collider environment without explicit particle identification.

The data used in this analysis were collected with the Collider Detector at Fermilab (CDF) during the 1992–1993 run, and correspond to an integrated luminosity of 19.3 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The CDF detector is described in detail elsewhere [12]. The silicon vertex detector (SVX) and the central tracking chamber (CTC) provide spatial measurements in the r-φ plane [13], giving a track impact parameter resolution of $(13 + 40/P_T)$ μm [14]. The P_T resolution of the CTC combined with the SVX is $\delta(P_T)/P_T = [(0.0066)^2 + (0.0009P_T)^2]^{1/2}$. Two muon subsystems in the central region were used, which together provide coverage in the interval $|\eta| < 1.0$, where $\eta = -\ln[\tan(\theta/2)]$. Dimuon events were collected using a three-level trigger system. The trigger requires that two oppositely charged CTC tracks each match muon track segments and that the $\mu^+\mu^-$ invariant mass is between 2.8 and 3.4 GeV$/c^2$ to select J/ψ candidates [11].

The B meson reconstruction starts with the isolation of the J/ψ signal. First, the CTC track is extrapolated to the muon chambers and is required to match the muon track segment. Only well measured tracks in the CTC are used and good quality SVX information is added when available, which is in approximately 50% of the candidates. We calculate the invariant mass of two oppositely charged muon candidates after constraining them to originate from a common point in space ("vertex constraint"). The confidence level (C.L.) of the fit is required to be greater than 1%. We require one muon with $P_T > 1.8$ GeV$/c$ and the other one with $P_T > 2.5$ GeV$/c$ to ensure we operate in a well-measured region of the trigger efficiency. We find $62\,146 \pm 299$ J/ψ meson candidates with a signal-to-background ratio of 5:1.

After mass constraining the J/ψ to the world average value [15] and requiring the C.L. $> 1\%$, we search for kaon candidates from all other tracks within the CTC fiducial volume. For the $J/\psi K^+$ mode, every track is considered a kaon candidate. The K_S^0 selection requires two oppositely charged tracks with $P_T > 0.35$ GeV$/c$, each track satisfying $d_\pi/\sigma_{d_\pi} > 2$, where d_π is the distance of closest approach to the beam position, and σ_{d_π} is the uncertainty. The $\pi^+\pi^-$ pairs are vertex constrained, required to point to the J/ψ vertex and satisfy the requirement, C.L. $> 1\%$. A signed two-dimensional decay length $L_{xy}(K_S^0) > 1.0$ cm, defined as the displacement of the K_S^0 vertex projected onto the direction of the $P_T(K_S^0)$, is required. We find 7733 ± 101 K_S^0 candidates with a signal-to-background ratio of 7:1. The $K^*(892)^+$ candidate is formed with a K_S^0 candidate plus a track, assumed to be a π^+, and the $K^*(892)^0$ candidate is formed from two charged tracks assumed to be a K^+ and a π^-. The K-π particle assignment with invariant mass closest to the world average mass [15] of the $K^*(892)^0$ is retained and combinations where the K^* mass is greater than 75 MeV$/c^2$ from the world average mass are rejected.

In order to maximize the combinatoric background rejection, several constraints are applied incrementally and for each added constraint we require C.L.$(\Delta\chi^2) > 1\%$, where $\Delta\chi^2$ is the change in χ^2 due to the additional constraint. For the $J/\psi K^+$ mode, the K^+ candidate track is added to the J/ψ vertex constraint. For the $J/\psi K_S^0$ mode, K_S^0 decay products are vertex and mass constrained and the K_S^0 is constrained to point to the J/ψ vertex in three dimensions. For the $J/\psi K^*(892)^+$ mode, the K_S^0 is constrained to point to the three-track $J/\psi \pi^+$ vertex and for the $J/\psi K^*(892)^0$ mode, the four tracks are vertex constrained. For all four modes, the B candidate system is constrained to point to the primary vertex.

To further reduce the combinatoric background, we require $P_T(K^*) > 1.5$ GeV$/c$, $P_T(B) > 7$ GeV$/c$, and $c\tau(B) > 100$ μm, where $c\tau(B)$ is computed using the displacement of the J/ψ vertex projected onto the direction of the $P_T(B)$. The normalized mass distributions are shown in Fig. 1 for $J/\psi K^+$ and $J/\psi K_S^0$, and in Fig. 2 for the $J/\psi K^*(892)^0$ and $J/\psi K^*(892)^+$. The normalized mass is computed for each candidate by dividing the difference between the invariant mass and the world

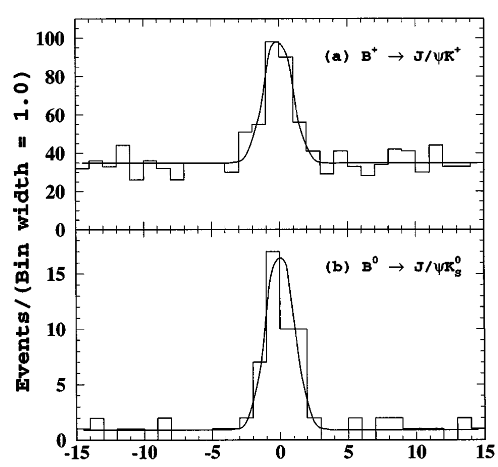

FIG. 1. The normalized mass distribution for (a) $J/\psi K^+$ and (b) $J/\psi K_S^0$ after all cuts.

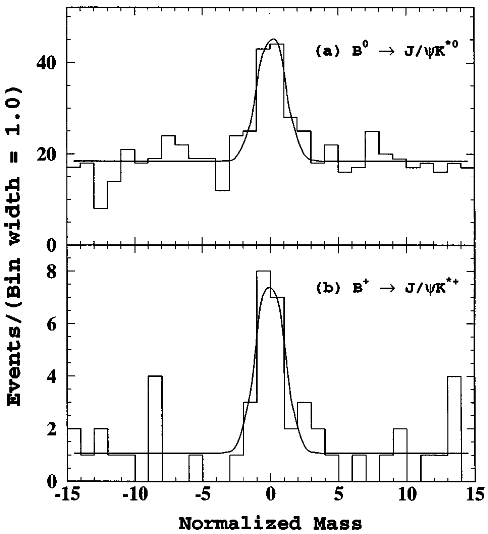

FIG. 2. The normalized mass distribution for (a) $J/\psi\, K^*(892)^0$ and (b) $J/\psi\, K^*(892)^+$ after all cuts.

average B mass [15] by the error on the mass (typically 12 MeV$/c^2$), where the error is determined using the full covariance matrix for each candidate. The normalized mass follows a Gaussian shape more closely than the invariant mass distribution. The number of signal events is obtained by fitting a Gaussian of width fixed to 1.0 and a flat background to the normalized mass distributions using a binned maximum likelihood method. The results are given in Table I.

The ratio of branching ratios is computed using the relation

$$\frac{B(B^0 \to J/\psi\, K^0)}{B(B^+ \to J/\psi\, K^+)} = \frac{2N(J/\psi\, K_S^0)}{N(J/\psi\, K^+)} \frac{\epsilon_{J/\psi\, K^+}}{\epsilon_{J/\psi\, K_S^0}} \times \frac{1}{B(K_S^0 \to \pi^+\pi^-)},$$

where the factor of 2 corrects for $K^0 \to K_L^0$, which is not reconstructed, and we assume equal production rates of B^+ and B^0 mesons. World average branching ratios are used for all K^* daughter decays [15], an isospin analysis determines $B(K^*(892)^0 \to K^+\pi^-) = 2/3$ and $B(K^*(892)^+ \to K^0\pi^+) = 2/3$.

The reconstruction efficiencies are factorized as

$$\epsilon_{J/\psi\, K^+} = \epsilon_{P_T(B)}\epsilon_{c\tau(B)}\epsilon_{J/\psi}\epsilon_{P_T(K^+)}\epsilon^R_{J/\psi\, K^+},$$
$$\epsilon_{J/\psi\, K_S^0} = \epsilon_{P_T(B)}\epsilon_{c\tau(B)}\epsilon_{J/\psi}\epsilon_{P_T(K_S^0)}\epsilon^R_{J/\psi\, K_S^0}.$$

The efficiency of the $P_T(B)$ cut ($\epsilon_{P_T(B)}$), the $c\tau(B)$ cut ($\epsilon_{c\tau(B)}$), the $P_T(K)$ cut ($\epsilon_{P_T(K)}$), and the efficiency for finding the J/ψ ($\epsilon_{J/\psi}$), all cancel in the ratio. However, some of the efficiencies associated with the K_S^0 decay do not cancel in the ratio. The superscript R denotes the remaining terms. To facilitate cancellation, these terms are factorized as

$$\epsilon^R_{J/\psi\, K^+} = \epsilon^G_{K^+}\epsilon_{\mathrm{Trk}(K^+)}\epsilon_{\Delta\chi^2(J/\psi\, K^+)},$$
$$\epsilon_{\Delta\chi^2(J/\psi\, K^+)} = \epsilon_{V(\mu^+\mu^-)}\epsilon_{M(\mu^+\mu^-)}\epsilon_{V(K^+)} \times \epsilon_{P_{xy}(J/\psi\, K^+)}\epsilon_{P_z(J/\psi\, K^+)}$$

and

$$\epsilon^R_{J/\psi\, K_S^0} = \epsilon_{K_S^0}\epsilon_{\Delta\chi^2(J/\psi\, K_S^0)},$$
$$\epsilon_{K_S^0} = \epsilon^G_{\pi}\epsilon_{P_T(\pi)}\epsilon_{\mathrm{Trk}(K_S^0)}\epsilon_{L_{xy}}\epsilon_{d_\pi},$$
$$\epsilon_{\Delta\chi^2(J/\psi\, K_S^0)} = \epsilon_{V(\mu^+\mu^-)}\epsilon_{M(\mu^+\mu^-)}\epsilon_{V(\pi^+\pi^-)}\epsilon_{P(\pi^+\pi^-)} \times \epsilon_{M(\pi^+\pi^-)}\epsilon_{P_{xy}(J/\psi\, K_S^0)}\epsilon_{P_z(J/\psi\, K_S^0)},$$

where the superscript G indicates the term is a geometrical acceptance, V, M, and P indicate a vertex, mass, or pointing constraint, respectively, while P_{xy} and P_z refer to pointing constraints in the x-y plane and z direction. We cancel the $\epsilon_{V(K^+)}$ against the $\epsilon_{P(\pi^+\pi^-)}$ term and have verified the cancellation by Monte Carlo simulation. Canceling the remaining terms in the expansion of $\epsilon_{\Delta\chi^2(J/\psi\, K^+)}$ against similar terms in $\epsilon_{\Delta\chi^2(J/\psi\, K_S^0)}$, leaves the efficiency product $\epsilon^R_{\Delta\chi^2(J/\psi\, K_S^0)} = \epsilon_{V(\pi^+\pi^-)}\epsilon_{M(\pi^+\pi^-)}$.

The geometrical acceptances, the $\epsilon_{P_T(\pi)}$ term, the tracking efficiencies (ϵ_{Trk}), and the $\epsilon_{L_{xy}}$ are calculated using a Monte Carlo simulation that incorporates the following.

(1) The b-quark P_T and rapidity distributions follow the next-to-leading order QCD [16] calculation with MRS D0 [17] proton structure functions.

(2) The $B^+ \to J/\psi\, K^+$ and the $B^0 \to J/\psi\, K^0$ decays involve a pseudoscalar-to-vector-pseudoscalar decay. In the J/ψ rest frame, the decay muons follow a $\sin^2\theta$ angular distribution with respect to the kaon direction in the rest frame of the B meson.

(3) We measure the efficiency of the CTC track reconstruction algorithm by embedding simulated tracks in real data J/ψ events. The tracks are generated so as to permit the reconstruction of the B mass [2]. We measure a tracking efficiency of $\epsilon_{\mathrm{Trk}(K^+)} = [92.0 \pm 2.0(\mathrm{syst})]\%$ for $P_T(K^+) > 1.5$ GeV$/c$. The K_S^0 tracking efficiency is $\epsilon_{\mathrm{Trk}(K_S^0)} = [86.0 \pm 2.0(\mathrm{syst})]\%$ for $P_T(\pi) > 0.35$ GeV$/c$.

TABLE I. Summary of number of events, signal-to-background (S/B), and ratios of efficiencies relative to the $B^+ \to J/\psi\, K^+$ decay mode.

	$J/\psi\, K^+$	$J/\psi\, K_S^0$	$J/\psi\, K^*(892)^0$	$J/\psi\, K^*(892)^+$
Number of events	169 ± 18	41.8 ± 6.9	71 ± 12	17.0 ± 4.7
S/B	0.97	9.23	0.77	3.12
Ratio of efficiencies	⋯	1.57 ± 0.08	2.11 ± 0.18	3.53 ± 0.37

The efficiency of the $d_\pi/\sigma_{d_\pi} > 2$ cut and the efficiencies of the C.L.$(\Delta\chi^2) > 1\%$ requirement on the vertex and mass constraints of the $\pi^+\pi^-$ pairs ($\epsilon_{V(\pi^+\pi^-)}$, $\epsilon_{M(\pi^+\pi^-)}$) were obtained from the inclusive K_S^0 sample. In summary, we determine the ratio of efficiencies to be $\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K_S^0} = 1.57 \pm 0.08(\mathrm{syst})$.

For the $J/\psi K^*(892)^0$ and the $J/\psi K^*(892)^+$ decay modes, the efficiencies are factorized in the same manner. For both ratios, $[J/\psi K^*(892)^0]/(J/\psi K^+)$ and $[J/\psi K^*(892)^+]/(J/\psi K^+)$, the efficiencies for the cuts on $c\tau(B)$ and $P_T(B)$ will cancel.

The efficiency of the $P_T(K^*)$ cut and finding the J/ψ do not cancel because of the K^* polarization and the K^*-K mass difference. These ratios are corrected for the acceptance of the K^* mass window, which is computed by integrating a Breit-Wigner distribution. Each $(J/\psi K^*)/(J/\psi K^+)$ ratio also has unique noncanceling efficiencies. For the $K^*(892)^0$ case, there is the effect of slightly different geometrical acceptances and efficiencies for the K^+, as well as terms associated with the π^-: the efficiency of adding an extra track to the vertex constraint, the $P_T(\pi)$ cut, and the track and geometric efficiencies.

For the $[J/\psi K^*(892)^+]/(J/\psi K^+)$ ratio, both modes have a charged track originating from the B decay vertex. However, the geometric acceptance, track reconstruction, kinematic and C.L.$(\Delta\chi^2)$ cut efficiencies are slightly different. The efficiencies associated with the K_S^0 are determined in the same manner outlined previously. We use the Monte Carlo method described above to compute the ratio of the remaining efficiencies. A summary is provided in Table I.

Six sources of systematic uncertainty contribute to the ratio of efficiencies. Each uncertainty in the lifetimes, τ_{B^+} and τ_{B^0}, contributes a 2% uncertainty to the $c\tau(B) > 100\ \mu$m cut. This contributes a 2.8% systematic error for the ratio of efficiencies. The ratio of tracking efficiencies has a (2–3.5)% systematic error, depending on the mode. The C.L.$(\Delta\chi^2) > 1\%$ requirement adds (2–2.8)% and was determined from the inclusive K_S^0 sample. Polarization (Γ_L/Γ) uncertainties contribute (1.9–2.4)% and the variation of the b-quark P_T spectrum in the Monte Carlo simulation contributes (1.7–7.6)%. In the two cases where the J/ψ trigger efficiencies do not cancel due to different polarization effects in the ratio, we determine the ratio of the number of events with and without a trigger requirement, and assign an additional 5% uncertainty due to the difference in the ratios. The uncertainties are summarized in Table II.

We find the ratios of branching ratios to be

$$B(B^0 \to J/\psi K^0)/B(B^+ \to J/\psi K^+) = 1.13 \pm 0.22(\mathrm{stat}) \pm 0.06(\mathrm{syst}),$$
$$B(B^0 \to J/\psi K^*(892)^0)/B(B^+ \to J/\psi K^+) = 1.33 \pm 0.27(\mathrm{stat}) \pm 0.11(\mathrm{syst}),$$
$$B(B^+ \to J/\psi K^*(892)^+)/B(B^+ \to J/\psi K^+) = 1.55 \pm 0.46(\mathrm{stat}) \pm 0.16(\mathrm{syst}).$$

We determine the vector-pseudoscalar ratio using the relation

$$R = \frac{[N(J/\psi K^{*0}) + N(J/\psi K^{*+})]/(\nu_0 \epsilon^T_{J/\psi K^{*0}} + \nu_+ \epsilon^T_{J/\psi K^{*+}})}{[N(J/\psi K_S^0) + N(J/\psi K^+)]/(\nu_0 \epsilon^T_{J/\psi K_S^0} + \nu_+ \epsilon^T_{J/\psi K^+})},$$

where we have assumed isospin symmetry. The symbol ϵ^T represents the total reconstruction efficiency including all branching ratios while ν_+ and ν_0 are factors which depend on the ratio of production rates and the B meson lifetime ratio (τ_{B^+}/τ_{B^0}). Assuming equal production rates, we determine

$$R = \Gamma(B \to J/\psi K^*)/\Gamma(B \to J/\psi K) = 1.32 \pm 0.23(\mathrm{stat}) \pm 0.16(\mathrm{syst}),$$

where the systematic error is summarized in Table II. The dominant systematic uncertainty of 9% comes from τ_{B^+}/τ_{B^0} [15]. In addition we use the world average value $B(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$ [15] to obtain three

TABLE II. Summary of systematic uncertainties (%) for the ratios of branching ratios.

	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K_S^0}$	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K^{*0}}$	$\epsilon_{J/\psi K^+}/\epsilon_{J/\psi K^{*+}}$	ϵ_V/ϵ_P
τ_{B^+}/τ_{B^0}	2.8	2.8	⋯	9
Trk efficiency	2.8	2	3.5	2.1
C.L.$(\Delta\chi^2)$	2.8	2	3.5	2.1
Γ_L/Γ	⋯	1.9	2.4	1.9
$P_T(b)$ variations	1.7	5.4	7.6	5.5
Trigger	⋯	5	5	5
Total	5.0%	8.6%	10.6%	12%

branching ratios

$$B(B^0 \to J/\psi\, K^0) = [1.15 \pm 0.23(\mathrm{stat}) \pm 0.17(\mathrm{syst})] \times 10^{-3},$$
$$B\,(B^0 \to J/\psi\, K^*(892)^0) = [1.36 \pm 0.27(\mathrm{stat}) \pm 0.22(\mathrm{syst})] \times 10^{-3},$$
$$B\,(B^+ \to J/\psi K^*(892)^+) = [1.58 \pm 0.47(\mathrm{stat}) \pm 0.27(\mathrm{syst})] \times 10^{-3},$$

where the quoted systematic error includes the uncertainty in the $B(B^+ \to J/\psi\, K^+)$. These results are consistent with the current world average values [15].

In conclusion, we have presented the details of the reconstruction of the CP eigenstate $B^0 \to J/\psi\, K_S^0$ in a hadron collider environment and demonstrated that a good signal-to-background ratio is achieved. We have reported three branching ratios using $B^0 \to J/\psi\, K^*(892)^0$, $B^+ \to J/\psi\, K^*(892)^+$, and $B^0 \to J/\psi\, K^0$ relative to $B^+ \to J/\psi\, K^+$, which are comparable in precision and in good agreement with the current world average values [15].

We also combine these four decay modes to determine the vector-pseudoscalar ratio and confirm a previous determination of $R = 1.64 \pm 0.34$ [18], where naive spin counting would predict a value of three for the vector-pseudoscalar ratio. Theoretical models [6–8] that assume the factorization hypothesis and use current meson form factors are presently not able to simultaneously accommodate a low vector-pseudoscalar ratio and the polarization data [5]. This measurement reinforces the need for a better understanding of these models.

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