Measurement of the Relative Branching Fraction of $\Upsilon(4S)$ to Charged and Neutral B-Meson Pairs

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(Received 1 June 2000)

We analyze 9.7×10^6 $B\overline{B}$ pairs recorded with the CLEO detector to determine the production ratio of charged to neutral B-meson pairs produced at the $\Upsilon(4S)$ resonance. We measure the rates for $B^0 \to J/\psi K^{(*)0}$ and $B^+ \to J/\psi K^{(*)+}$ decays and use the world-average B-meson lifetime ratio to extract the relative widths $\frac{f_{+-}}{f_{00}} = \frac{\Gamma(\Upsilon(4S)\to B^+B^-)}{\Gamma(\Upsilon(4S)\to B^0\overline{B}^0)} = 1.04 \pm 0.07(\text{stat}) \pm 0.04(\text{syst})$. With the assumption that $f_{+-} + f_{00} = 1$, we obtain $f_{00} = 0.49 \pm 0.02(\text{stat}) \pm 0.01(\text{syst})$ and $f_{+-} = 0.51 \pm 0.02(\text{stat}) \pm 0.01(\text{syst})$. This production ratio and its uncertainty apply to all exclusive B-meson branching fractions measured at the $\Upsilon(4S)$ resonance.

DOI: 10.1103/PhysRevLett.86.2737 PACS numbers: 14.40.Nd, 13.25.Hw

Measurements of exclusive B-decay branching fractions from e^+e^- collider operation at the $\Upsilon(4S)$ resonance assume equal production rates of charged and neutral B-meson pairs [1]. In the literature, the uncertainty in a specific branching fraction due to a lack of knowledge of the production ratio is often ignored.

Any physics based upon comparisons of absolute decay rates of charged and neutral B mesons will profit from a more precise knowledge of the B-production ratio, $f_{+-}/f_{00} \equiv \Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\overline{B}^0)$. For example, a comparison of the branching fractions of two-body hadronic decays can be used to obtain information on the relative contributions from external and internal spectator decays. (External spectators have the virtual W^- transform into a single meson, while internal spectators have the quark from the W^- combine with the spectator-antiquark, thus requiring matching colors.) For all exclusive decay modes studied, the B^+ branching fraction was found to be larger than the corresponding B^0 branching fraction, indicating constructive interference between the external and internal spectator amplitudes. This is in contrast to the destructive interference observed in hadronic charm decay [2]. The magnitude of the constructively interfering fraction depends on the value of f_{+-}/f_{00}. Another application of the f_{+-}/f_{00} ratio arises in the use of ratios of charmless hadronic B-decay rates [3] to set bounds on the angle γ, the phase of the Cabibbo-Kobayashi-Maskawa matrix element V_{ub} [1,4]. The uncertainty of f_{+-}/f_{00} contributes to the systematic uncertainty of the γ bound.

A better measurement of f_{+-}/f_{00} would also allow a more meaningful comparison with theoretical predictions of the relative B^+B^- and $B^0\overline{B}^0$ production rates at the $\Upsilon(4S)$ resonance. If there are no other important differences between the two $\Upsilon(4S)$ decays, such as $B^+ - B^0$ mass splitting or isospin-violating form factors in the decay amplitude, Coulomb corrections to B^+B^- production near threshold are not negligible, giving rise to $\frac{\Gamma(\Upsilon(4S)\to B^+B^-)}{\Gamma(\Upsilon(4S)\to B^0\overline{B}^0)} \simeq 1.18$ [5]. Other authors [6] argue that the B-meson substructure cannot be ignored and strongly reduces the Coulomb effect in the B-production ratio to 1.05–1.07, depending on the B masses and momenta.

Existing measurements of the admixture ratio of charged to neutral B mesons produced at the $\Upsilon(4S)$ resonance have an uncertainty of $\sim$15%. One measurement [7] used the branching-fraction ratio of $\mathcal{B}(B^+ \to J/\psi K^{(*)+})$ to $\mathcal{B}(B^0 \to J/\psi K^{(*)0})$ [8] to yield $\frac{f_{+-}}{f_{00}} \times \frac{\tau_{B^+}}{\tau_{B^0}} = 1.15 \pm 0.17 \pm 0.06$, where the first uncertainty is statistical, the second is systematic, and τ_B denotes the B lifetime. Another measurement [9] used a ratio of $B \to D^* l \nu$ decays to extract $\frac{f_{+-}}{f_{00}} \times \frac{\tau_{B^+}}{\tau_{B^0}} = 1.14 \pm 0.14 \pm 0.13$.

In the present analysis, we study the decays $B \to J/\psi K^{(*)}$, which are isospin conserving transitions, since the J/ψ daughter is an isosinglet and the B and $K^{(*)}$ mesons are both iso-doublets. The decays $B^+ \to J/\psi K^{(*)+}$ and $B^0 \to J/\psi K^{(*)0}$ must therefore have equal partial widths, and we can extract $R \equiv \frac{f_{+-}}{f_{00}} \times \frac{\tau_{B^+}}{\tau_{B^0}} = \frac{\mathcal{N}(B^+\to J/\psi K^{(*)+})}{\mathcal{N}(B^0\to J/\psi K^{(*)0})}$, where $\mathcal{N}$ is the efficiency-corrected signal yield. Using the ratio of two similar decay rates to extract R, we exploit the cancellation of common experimental uncertainties. Throughout this Letter, reference to charge conjugate states is implicit.

The data analyzed in this study were recorded at the Cornell Electron Storage Ring (CESR) with two configurations of the CLEO detector, CLEO II and CLEO II.V. The data consist of an integrated luminosity of 9.2 fb^{-1} of e^+e^- annihilations recorded at the $\Upsilon(4S)$ resonance and of 4.6 fb^{-1} taken in the continuum, 60 MeV below the $\Upsilon(4S)$ energy. The results in this Letter are based upon 9.7×10^6 $B\overline{B}$ candidates and supersede those of Ref. [7].

The components of the CLEO detector most relevant to this analysis are the charged-particle tracking system, the 7800-crystal CsI electromagnetic calorimeter, and the muon chambers. The first third of the data was collected with the CLEO II detector [10], which measured the momenta of charged particles in a tracking system consisting of an inner 6-layer straw-tube chamber, a 10-layer precision drift chamber, and a 51-layer main drift chamber, all operating inside a 1.5 T solenoidal magnet. The main drift chamber also provided a measurement of the specific ionization loss (dE/dx) used in particle identification. Two-thirds of the data were taken with the CLEO II.V configuration, for which the innermost straw-tube chamber was replaced with a 3-layer silicon vertex detector

[11], and the argon-ethane gas of the main drift chamber was replaced with a helium-propane mixture. The muon identification system in both the CLEO II and CLEO II.V configurations consisted of proportional counters placed at various depths in the return yoke of the magnet.

Since the backgrounds for $B \to J/\psi K^{(*)}$ decays are very low, track and photon quality requirements have been designed to maximize signal yield. We reconstruct $B \to J/\psi K^{(*)}$ candidates in the data samples taken at the $\Upsilon(4S)$ energy.

Candidate J/ψ mesons are reconstructed in their leptonic decay modes, requiring J/ψ lepton daughter tracks to have momenta larger than 800 MeV$/c$. For J/ψ reconstruction in the muon channel, one of the muon candidates was required to penetrate the steel absorber to a depth greater than three nuclear interaction lengths. For the opposite sign daughter candidate, no muon detection requirement was imposed. Electron candidates were identified based on the ratio of the track momentum to the associated shower energy in the CsI calorimeter and specific ionization loss in the drift chamber. Bremsstrahlung produces a radiative tail in the e^+e^- invariant mass distribution below the J/ψ pole. We recovered some of the resultant efficiency loss by detecting the radiated photon. We selected photon candidates ($E_\gamma > 10$ MeV) with the smallest angle to the $e^\pm$ track, provided this angle did not exceed 5°. The $J/\psi \to e^+e^-$ efficiency was increased by ~20%, without adding background. We reconstructed 15 900 ± 700 inclusive $J/\psi \to l^+l^-$ candidates (Fig. 1), about equally shared in the two dilepton reconstruction modes. The resolution in the J/ψ invariant mass was ~13 MeV.

We required the dimuon invariant mass to be within 50 MeV of the world-average J/ψ mass [1], corresponding to a ~3.5 standard deviation (σ) selection. For the dielectron invariant mass we required $-150 \text{ MeV} < (m_{ee} - m_{J/\psi}) < 50$ MeV to allow for the radiative tail. The J/ψ energy resolution was improved by a factor ~4 after performing a kinematic fit of the dilepton invariant mass to the J/ψ mass. We required J/ψ candidates to have momenta below 2 GeV$/c$, which is near the kinematic limit for J/ψ mesons originating from a B meson nearly at rest.

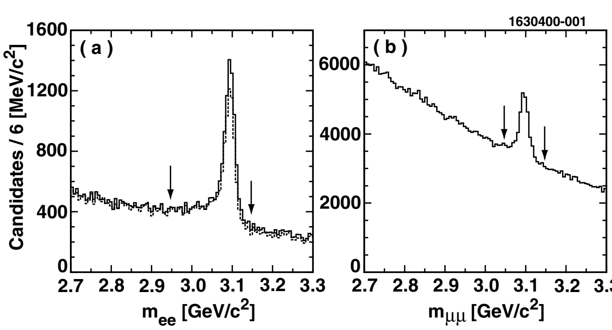

FIG. 1. Invariant mass spectrum of (a) $J/\psi \to e^+e^-$ and (b) $J/\psi \to \mu^+\mu^-$ candidates. The dashed line in (a) shows the mass spectrum before the addition of bremsstrahlung photons. The arrows delimit the J/ψ candidate region.

The $K_S^0 \to \pi^+\pi^-$ candidates were selected from pairs of tracks forming well-measured displaced vertices. The resolution in $\pi^+\pi^-$ invariant mass is approximately 2.5 MeV. Because of very low background in $B \to J/\psi K_S^0$ candidates, we require only neutral kaon candidates satisfying $(m_{\pi\pi} - m_{K_S^0})/\sigma(m_{\pi\pi}) \le 10$ (because the K_S^0 mass distribution has non-negligible non-Gaussian tails) and a normalized flight distance greater than zero.

Charged-kaon and -pion candidates are required to have a measured dE/dx within 3σ of the energy loss expected for the given particle type. Neutral pions are reconstructed from photon pairs detected within the barrel region of the CsI calorimeter, $|\cos\theta_\gamma| < 0.71$, where θ_γ is the polar angle of the candidate photon with respect to the e^+e^- beam axis. The photons must have a minimum energy of 30 MeV and π^0 candidates are required to have $m_{\gamma\gamma}$ within 2.5σ of the π^0 mass. This $\gamma\gamma$ invariant mass is then kinematically constrained to the π^0 mass. Charged and neutral pions and kaons are used to reconstruct the four K^* decay modes. Candidate K^* mesons are required to have a $K\pi$ invariant mass within 75 MeV of the world-average K^* mass [1,8].

We fully reconstruct B-meson candidates by employing the kinematics of a $B\overline{B}$ pair produced almost at rest. We use the energy difference $\Delta E \equiv E(J/\psi) + E(K^{(*)}) - E_{\text{beam}}$ as well as the beam-constrained mass $M(B) \equiv \sqrt{E_{\text{beam}}^2 - p^2(B)}$ as selection observables. The resolution in ΔE is 15 MeV for $J/\psi K^*$ with a π^0 candidate in the final state and 9–11 MeV for the other modes. We find the resolution in $M(B)$ to be ~2.5 MeV, which is

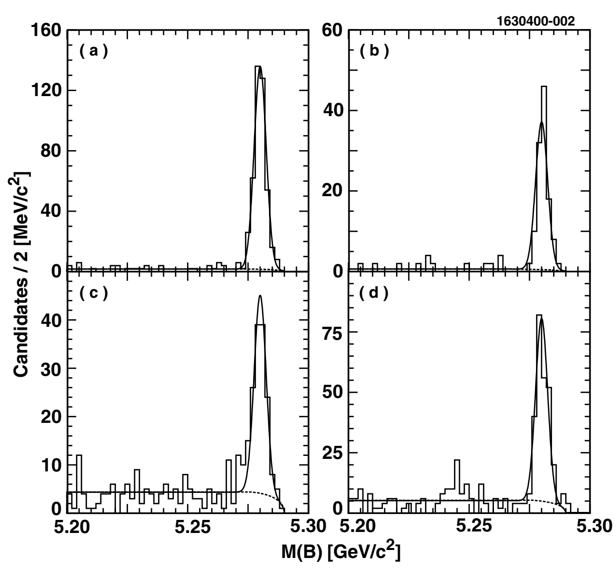

FIG. 2. Beam-constrained mass projections (histograms) for candidates in the ΔE signal region are shown for the entire data sample summed over both $J/\psi \to l^+l^-$ modes. The fits to the data are shown with the solid curves while the background fits are given with the dashed curves. Shown are distributions for (a) $B^+ \to J/\psi K^+$, (b) $B^0 \to J/\psi K_S^0$, (c) $B^+ \to J/\psi K^{*+}$, and (d) $B^0 \to J/\psi K^{*0}$ candidates.

TABLE I. Summary of reconstruction efficiencies (daughter branching fractions not included), cross-feed corrected signal yields (first error is statistical, second error is systematic), and branching fractions $\mathcal{B}$ computed from these yields and efficiencies (errors are statistical only), assuming equal production of B^+B^- and $B^0\overline{B}^0$ pairs. The computed branching fractions agree with the world-average values [1].

	Efficiency [%]		Cross-feed corrected yield		$\mathcal{B}$
	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$	$[\times 10^{-3}]$
CLEO II					
$J/\psi K^+$	46.0 ± 0.7	56.2 ± 0.7	$87.6 \pm 9.4 \pm 1.3$	$121.9 \pm 11.3 \pm 1.5$	1.02 ± 0.07
$J/\psi K_S^0$	43.3 ± 0.6	51.9 ± 0.7	$32.9 \pm 5.7 \pm 0.5$	$24.0 \pm 5.1 \pm 0.3$	0.83 ± 0.12
$J/\psi K^{*+}(K_S^0\pi^+)$	28.0 ± 0.6	34.1 ± 0.7	$13.1 \pm 3.8 \pm 0.3$	$15.9 \pm 4.6 \pm 0.3$	1.02 ± 0.21
$J/\psi K^{*+}(K^+\pi^0)$	16.5 ± 0.4	20.7 ± 0.4	$17.1 \pm 4.7 \pm 0.7$	$23.6 \pm 6.2 \pm 0.5$	1.63 ± 0.31
$J/\psi K^{*0}(K^+\pi^-)$	33.5 ± 0.5	40.6 ± 0.5	$53.1 \pm 7.5 \pm 0.8$	$56.8 \pm 8.0 \pm 0.7$	1.11 ± 0.11
$J/\psi K^{*0}(K_S^0\pi^0)$	16.4 ± 0.4	18.7 ± 0.4	$3.4 \pm 2.3 \pm 0.2$	$5.1 \pm 3.0 \pm 0.2$	1.02 ± 0.46
CLEO II.V					
$J/\psi K^+$	43.6 ± 0.7	58.8 ± 0.8	$172.5 \pm 13.1 \pm 2.8$	$210.2 \pm 15.0 \pm 2.9$	0.98 ± 0.05
$J/\psi K_S^0$	42.5 ± 0.5	57.9 ± 0.6	$42.5 \pm 6.5 \pm 0.6$	$78.9 \pm 9.1 \pm 0.9$	0.90 ± 0.08
$J/\psi K^{*+}(K_S^0\pi^+)$	28.6 ± 0.6	36.4 ± 0.7	$17.0 \pm 4.6 \pm 0.5$	$47.6 \pm 7.3 \pm 0.9$	1.00 ± 0.14
$J/\psi K^{*+}(K^+\pi^0)$	14.8 ± 0.4	21.6 ± 0.4	$35.9 \pm 6.8 \pm 1.0$	$42.0 \pm 8.2 \pm 1.0$	1.69 ± 0.23
$J/\psi K^{*0}(K^+\pi^-)$	31.1 ± 0.7	41.1 ± 0.8	$92.5 \pm 9.8 \pm 2.1$	$105.8 \pm 11.1 \pm 2.1$	1.08 ± 0.08
$J/\psi K^{*0}(K_S^0\pi^0)$	15.5 ± 0.5	18.2 ± 0.5	$11.9 \pm 4.0 \pm 0.5$	$8.6 \pm 4.0 \pm 0.4$	1.37 ± 0.38

dominated by the beam energy spread. We select signal candidates by requiring 5.2 GeV $< M(B) <$ 5.3 GeV and $|\Delta E| < 3\sigma_{\Delta E}$. The beam-constrained mass distributions for events within the ΔE signal region are shown in Fig. 2.

We extract the signal yield in each mode by performing a binned maximum-likelihood fit to the $M(B)$ projection, where the signal is given by a single Gaussian distribution with a fixed mean of 5.28 GeV and a fixed width of 2.5 MeV. The background is fit to a first-order polynomial joined with an elliptic function to fit the threshold nature of the beam-constrained mass distribution. The $M(B)$ distributions in the ΔE sideband regions exhibit a slope consistent with zero. These sideband regions are at least $4\sigma_{\Delta E}$ and less than one pion mass away from the ΔE signal region. We fix the slope of the background shape to zero and allow the level of the combinatoric background to be determined from the fit to the $M(B)$ projection of the ΔE signal region.

We must account for the individual final states being reconstructed in a different channel (cross-feed), since for such candidates both the total energy and the beam-constrained mass lie near the signal region. We evaluate the reconstruction efficiency, as well as the amount of cross-feed from a given channel i to another channel j, by using a sample of simulated $B \to J/\psi K_i^{(*)}$ events to generate a 6×6 efficiency matrix for the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ cases, as well as for CLEO II and CLEO II.V, separately. The CLEO detector simulation is based upon GEANT [12]. Simulated events are processed in a manner similar to that for the data. There is negligible cross-feed between the $J/\psi K$ and the $J/\psi K^*$ modes. The cross-feed into $J/\psi K^*$ modes with a charged-pion K^* daughter is near 5%, whereas cross-feed into $J/\psi K^*$ modes with a neutral-pion K^* daughter ranges between 8%–30% of the raw yield. Efficiencies and cross-feed corrected yields are listed in Table I. As a cross check, we also quote the branching fractions computed for the analyzed $B \to J/\psi K^{(*)}$ decays. We extract our result from the cross-feed and reconstruction-efficiency corrected yields and obtain four independent measurements of R listed in Table II.

We evaluate the uncertainties in the reconstruction efficiency due to track finding, track fitting, charged hadron identification, K_S^0 finding, and π^0 finding. Since we use the ratio of two decay rates that each involve $J/\psi \to l^+l^-$ candidates, uncertainties in lepton identification are negligible. We estimate the full systematic bias due to daughter reconstruction efficiency uncertainties by taking into account the correlations between the different final states in the numerator and denominator, resulting in some cancellation. By propagating these uncertainties through the weighted average of the results in Table II, we arrive at a systematic uncertainty on R due to the understanding of reconstruction efficiencies of $^{+1.0\%}_{-1.5\%}$. The polarization of the decay $B \to J/\psi K^*$ is modeled in our simulation with a longitudinal polarization fraction of $\Gamma_L/\Gamma = 0.52$ in accordance with Ref. [7]. We estimate the impact of the value used for Γ_L/Γ on the $B \to J/\psi K^*$ efficiencies by generating signal events with the nominal polarization varied by $\pm 1\sigma$ (± 0.08). The central value for R changes by less than 0.8% due to this variation. We vary the B candidate signal width by ± 0.2 MeV and estimate the

TABLE II. Results for $R = \frac{f_{+-}}{f_{00}} \times \frac{\tau_{B^+}}{\tau_{B^0}}$ for the different CLEO configurations and the $J/\psi K$ and $J/\psi K^*$ modes. The uncertainties are statistical.

Signal mode/Configuration	CLEO II	CLEO II.V
$B \to J/\psi K$	1.229 ± 0.191	1.088 ± 0.116
$B \to J/\psi K^*$	1.098 ± 0.190	1.095 ± 0.137

systematic uncertainty from this source to be less than 0.5%. We extract the signal yield using a background function that allows for a slope in the nonsignal region of the beam-constrained mass distribution and assign a systematic bias of 3% on the central value for R from our assumption of flat background. We attribute a 1.1% uncertainty to limited statistics of the simulated event samples used to extract the efficiency matrices. We find a better than 15% rms. agreement in the inclusive neutral-pion spectrum between data and simulation. A $\pm 15\%$ variation of the cross-feed into the neutral-pion $J/\psi K^*$ sample changes R by up to 1.4%. Adding all contributions in quadrature we obtain a total systematic uncertainty of $^{+3.8\%}_{-4.0\%}$ on R.

We weigh the results of Table II with their statistical uncertainty and, combined with the estimated systematic uncertainty, we extract

$$R \equiv \frac{f_{+-}}{f_{00}} \times \frac{\tau_{B^+}}{\tau_{B^0}} = 1.113 \pm 0.069\,^{+0.042}_{-0.045},$$

where the first uncertainty is statistical and the second is systematic.

Using the world-average lifetime ratio of charged- and neutral-B mesons, 1.066 ± 0.024 [13], we obtain a measurement of the production ratio

$$\frac{f_{+-}}{f_{00}} = \frac{\Gamma(\Upsilon(4S) \to B^+B^-)}{\Gamma(\Upsilon(4S) \to B^0\overline{B}^0)}$$

and, assuming $f_{+-} + f_{00} = 1$, we also extract $f_{00} = 0.49 \pm 0.02 \pm 0.01$ and $f_{+-} = 0.51 \pm 0.02 \pm 0.01$.

We have measured the ratio of charged to neutral production of B mesons at the $\Upsilon(4S)$ resonance [14] to be $1.04 \pm 0.07 \pm 0.04$, which is consistent with unity within an error of 8%. This is the most precise measurement of f_{+-}/f_{00}. Our result is consistent with theoretical predictions of only slightly greater charged than neutral B-meson pair production in $\Upsilon(4S)$ decays near threshold [6]. We emphasize that the ratio f_{+-}/f_{00} and its uncertainty must be taken into account when performing measurements that compare charged- and neutral-B decays at the $\Upsilon(4S)$ resonance.

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Research Corporation, the Natural Sciences and Engineering Research Council of Canada, the A. P. Sloan Foundation, the Swiss National Science Foundation, and the Alexander von Humboldt Stiftung.

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