Measurement of Branching Fractions and Charge Asymmetries for Exclusive B Decays to Charmonium

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We report measurements of branching fractions and charge asymmetries of exclusive decays of neutral and charged B mesons into two-body final states containing a charmonium state and a light strange meson. The charmonium mesons considered are J/ψ, $\psi(2S)$ and χ_{c1}, and the light meson is either K or K^*. We use a sample of about 124×10^6 $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II storage ring at the Stanford Linear Accelerator Center.

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Nonleptonic decays of B mesons provide tests of both strong- and weak-interaction dynamics. Decays $B \rightarrow (c\bar{c})K^{(*)}$ are particularly illuminating as they involve three kinds of mesons: one with a heavy quark and a light quark, one with two heavy quarks, and one with two light quarks. A better description of the long distance nonpertubative aspects of QCD is indeed necessary to improve our understanding of heavy meson weak decays and more particularly our knowledge of the quark mixing matrix [1]. Phenomenological models (see Refs. [2–12] of Ref. [2]) give estimates for branching fractions and for ratios of the decays to K and K^*. Some branching fractions and ratios have been reported (early measurements can be found in [3,4]) but others have not, so more stringent tests of the models are possible. The standard model predicts small differences between the branching fractions for positive and negative B mesons, i.e., small direct CP violation [5]. Large charge asymmetries would be evidence for new physics. Limits on direct CP violation would constrain extensions of the standard model. Very few charge asymmetry measurements have been reported in $B \rightarrow (c\bar{c})K^{(*)}$ modes [6]. The decay processes studied in this Letter are listed in Table I.

The data sample used in this analysis contains 124×10^6 $B\overline{B}$ events collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. This represents a total integrated luminosity of $112.4\ \mathrm{fb}^{-1}$ taken on the $\Upsilon(4S)$ resonance. The *BABAR* detector is described in detail elsewhere [7]. Surrounding the interaction point, a five-layer double-sided silicon vertex tracker (SVT) provides precise reconstruction of track angles and B decay vertices. A 40-layer drift chamber (DCH) provides measurements of the transverse momenta of charged particles. An internally reflecting ring-imaging Cherenkov detector (DIRC) is used for particle identification. A CsI(Tl) crystal electromagnetic calorimeter (EMC) is used to detect photons and electrons. The calorimeter is surrounded by a 1.5-T magnetic field. The flux return is instrumented with resistive plate chambers (RPC) used for muon and neutral-hadron identification.

Multihadron events are selected by demanding a minimum of three reconstructed charged tracks in the polar-angle range $0.41 < \theta < 2.54$ rad, where θ is defined in the laboratory frame. Charged tracks must be reconstructed in the DCH and are required to originate within 1.5 cm of the beam in the plane transverse to it and within 10 cm of the beam spot along the beam direction. Events are required to have a primary vertex within 0.5 cm of the average position of the interaction point in the plane transverse to the beam line, and within 6 cm longitudinally. Charged tracks are required to include at least 12 DCH hits and to have a transverse momentum $p_T > 100\ \mathrm{MeV}/c$. Photons are reconstructed from EMC clusters. The lateral energy profile (LAT) [8] is used to discriminate electromagnetic from hadronic clusters. Photons are required to have a minimum energy of 30 MeV, to satisfy $\mathrm{LAT} < 0.8$, and to be in the fiducial volume $0.41 < \theta < 2.41$ rad. Electron candidates are selected using information from the EMC (LAT and Zernike moment A_{42} [9]), the ratio of the energy measured in the EMC to the momentum measured by the tracking system, the energy loss in the drift chamber, and the Cherenkov angle measured in the DIRC. Electrons are also required to be in the fiducial volume $0.41 < \theta < 2.41$ rad. Muon candidates are selected using information from the EMC (energy deposition consistent with a minimum ionizing particle) and the distribution of hits in the RPC. Muons are required to be in the fiducial volume $0.3 < \theta < 2.7$ rad. We select charged kaon and pion candidates using information from the energy loss in the SVT and DCH, and the Cherenkov angle measured in the DIRC. Kaon candidates are required to be in the fiducial volume $0.45 < \theta < 2.45$ rad.

The selection has been optimized by maximizing the ratio $S/\sqrt{S+B}$, where S and B are the number of expected signal and background events obtained from Monte Carlo simulation. The J/ψ candidates are required to have an invariant mass $2.95 < M_{e^+e^-} < 3.14\ \mathrm{GeV}/c^2$ or $3.06 < M_{\mu^+\mu^-} < 3.14\ \mathrm{GeV}/c^2$ for $J/\psi \rightarrow e^+e^-$ or $J/\psi \rightarrow \mu^+\mu^-$ decays, respectively. The $\psi(2S)$ candidates are required to have an invariant mass $3.44 < M_{e^+e^-} < 3.74\ \mathrm{GeV}/c^2$ or $3.64 < M_{\mu^+\mu^-} < 3.74\ \mathrm{GeV}/c^2$ for $\psi(2S) \rightarrow e^+e^-$ or $\psi(2S) \rightarrow \mu^+\mu^-$ decays, respectively.

TABLE I. Decay processes studied in this analysis. The $(c\bar{c})$ resonance is either a J/ψ, $\psi(2S)$, or χ_{c1}. For all processes, when relevant, we use the secondary-decay modes $J/\psi, \psi(2S) \rightarrow \ell^+\ell^-$, $\chi_{c1} \rightarrow J/\psi\gamma$, and $K^0_S \rightarrow \pi^+\pi^-$, $\pi^0 \rightarrow \gamma\gamma$.

Decay channel	Secondary K^* decay mode
$B^0 \rightarrow (c\bar{c})\ K^{*0}$	$K^{*0} \rightarrow K^+\pi^-, K^0_S\pi^0$
$B^+ \rightarrow (c\bar{c})\ K^{*+}$	$K^{*+} \rightarrow K^+\pi^0, K^0_S\pi^+$
$B^0 \rightarrow (c\bar{c})\ K^0_S$	
$B^+ \rightarrow (c\bar{c})\ K^+$	

For J/ψ, $\psi(2S) \to e^+e^-$ decays, electron candidates are combined with photon candidates in order to recover some of the energy lost through bremsstrahlung. In the χ_{c1} reconstruction, J/ψ candidates are selected as described above. The associated γ has to satisfy LAT < 0.8, $A_{42} < 0.15$ and has to have an energy greater than 0.15 GeV. The χ_{c1} candidates are required to satisfy $0.35 < M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-} < 0.45$ GeV$/c^2$, where ℓ represents an electron or a muon. The $\pi^0 \to \gamma\gamma$ candidates are required to satisfy $0.113 < M_{\gamma\gamma} < 0.153$ GeV$/c^2$. Both photons have to satisfy LAT < 0.8. The energy of the soft photon has to be greater than 0.050 GeV and the energy of the hard photon has to be greater than 0.150 GeV. The $K_S^0 \to \pi^+\pi^-$ candidates are required to satisfy $0.489 < M_{\pi^+\pi^-} < 0.507$ GeV$/c^2$. In addition, the K_S^0 flight distance defined as the distance between the reconstructed B and K_S^0 vertices must exceed 1 mm, and the angle between the K_S^0 momentum and its flight direction in the plane transverse to the beam axis must be less than 0.2 rad. The K^{*0} and K^{*+} candidates are required to satisfy $0.796 < M_{K\pi} < 0.996$ GeV$/c^2$ and $0.792 < M_{K\pi} < 0.992$ GeV$/c^2$, respectively. In addition, for the sake of suppressing background from events with soft pions, for channels having a π^0 in the final state, the cosine of the angle between the K momentum and the B momentum in the K^* rest frame has to be less than 0.8.

The B candidates are reconstructed by combining charmonium and kaon candidates and 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 $\Delta E = E_B^* - E_{\rm beam}^*$, and the beam energy-substituted mass $m_{\rm ES}$, defined as $m_{\rm ES} \equiv \sqrt{E_{\rm beam}^{*2} - \mathbf{p}_B^{*2}}$, where the $*$ refers to quantities in the center of mass and $\mathbf{p}_B$ is the B momentum. For a correctly reconstructed B meson, ΔE is expected to peak at zero and the energy-substituted mass $m_{\rm ES}$ at the B meson mass, 5.279 GeV$/c^2$. Only one reconstructed B meson is allowed per event. For events that have multiple candidates, the candidate having the smallest $|\Delta E|$ is chosen. The analysis is performed in a region of the $m_{\rm ES}$ vs ΔE plane defined by $5.2 < m_{\rm ES} < 5.3$ GeV$/c^2$ and $-0.12 < \Delta E < 0.12$ GeV. A ΔE channel-dependent signal region is subsequently defined. The $m_{\rm ES}$ distributions within the ΔE signal region for candidate events are shown on Fig. 1.

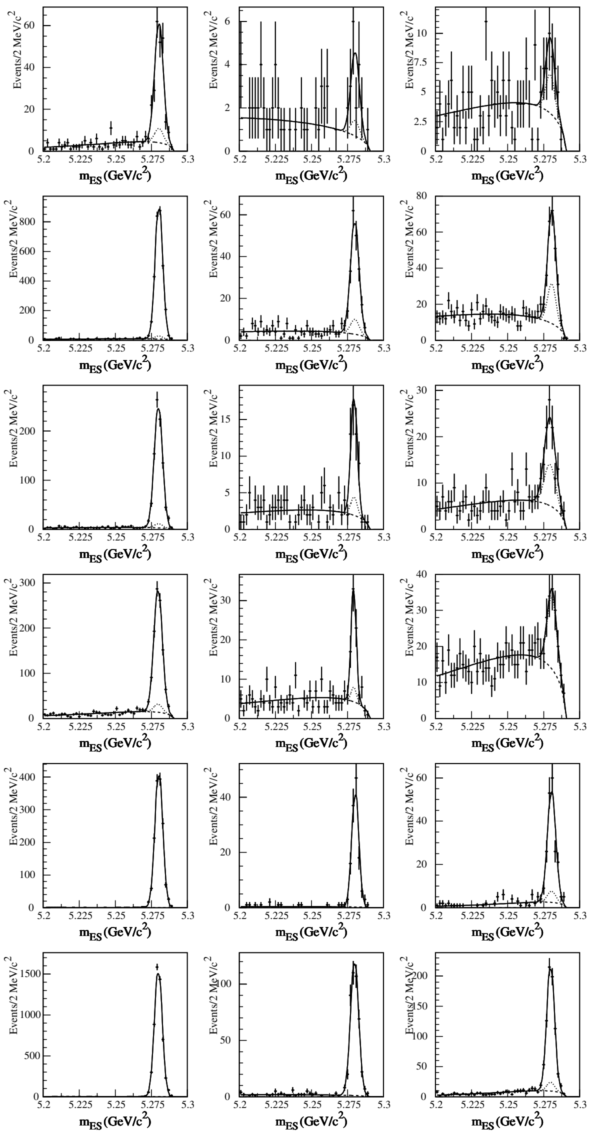

FIG. 1. $m_{\rm ES}$ distributions and fits within the ΔE signal region. From left to right, the columns show the distributions for the J/ψ, $\psi(2S)$, and χ_{c1} channels. From top to bottom, the rows show the distributions for the $B \to (c\bar{c})\ K^{*0}\ (K_S^0\pi^0)$, $B \to (c\bar{c})\ K^{*0}\ (K^+\pi^-)$, $B \to (c\bar{c})\ K^{*+}\ (K_S^0\pi^+)$, $B \to (c\bar{c})\ K^{*+}\ (K^+\pi^0)$, $B \to (c\bar{c})\ K_S^0$ and $B \to (c\bar{c})\ K^+$ decay modes. The dashed and dotted lines show the combinatorial and peaking backgrounds, respectively.

There are two components to the residual background in the ΔE signal region: the combinatorial background and a peaking component (component of the background that peaks at the same values of ΔE and $m_{\rm ES}$ as the signal). The number of signal events N_S is determined from the number of candidate events, $N_{\rm cand}$, after subtracting the peaking background. For this purpose, the $m_{\rm ES}$ distribution within the ΔE signal region is fitted to the sum of an ARGUS function [4], which models the combinatorial background, and a Gaussian function. The value of $N_{\rm cand}$ is given by the integral of the Gaussian component. There are two contributions to the peaking background. The first is the cross-feed component that is due to $B \to (c\bar{c})\ K^*$ events from the three channels other than the one under consideration. The second contribution is from other B decays with a J/ψ or $\psi(2S)$ in the final state. To determine the extent of peaking background, the $m_{\rm ES}$ distribution for simulated $B\overline{B}$ events is fitted within the ΔE signal region by an ARGUS function and a Gaussian function. The peaking background is taken as the integral of the Gaussian portion.

The branching fractions are obtained as

$$BF \equiv \frac{N_S}{N_{B\overline{B}} \times \epsilon \times f}, \qquad (1)$$

where $N_{B\overline{B}}$ is the number of $B\overline{B}$ events, ϵ is the selection efficiency, and f is the total secondary branching fraction. For channels with a K^* in the final state, the cross-feed contribution depends on the branching fractions that are being measured. It was estimated by an iterative procedure and found to be small.

The systematic errors arise from the uncertainty on the number of $B\overline{B}$ events (1.1%), the secondary branching fractions (taken from Ref. [10]), the estimate of the selection efficiency, and the knowledge of the background. For the tracking efficiency, an error of 1.3% per track has been used. For the particle identification efficiency, the systematic error varies between 0.2% and 3.7%. The uncertainty on the detection and energy measurement of photons is 2.5%, common to all channels, plus a small channel-dependent correction. The uncertainty on the π^0 reconstruction is 5.0% for all channels, plus a channel-dependent correction. The overall selection efficiency depends on the angular distribution. The efficiency can be written as $\epsilon = a + |A_0|^2 b$, where a and b are obtained from the K^* helicity angle by $a = 3/4 \int (1 - \cos^2\theta_{K^*})\epsilon(\theta_{K^*}) \times \sin(\theta_{K^*}) d\theta_{K^*}$ and $b = 3/4 \int (3\cos^2\theta_{K^*} - 1)\epsilon(\theta_{K^*}) \times \sin(\theta_{K^*}) d\theta_{K^*}$, and $|A_0|^2$ is the fraction of the longitudinal K^* polarization [11]. The values of a and b are obtained from simulation. Using an error for $|A_0|^2$ varying between 7% and 15% [11] depending on the final state, we obtain a systematic uncertainty on the efficiency and consequently on the branching fractions varying from 3.4% to 8.6%. In the default fit, the shape parameter of the ARGUS function is not constrained. To determine a systematic error due to the combinatorial background, a second fit with the shape parameter of the ARGUS function fixed to the value obtained from fitting the data in the ΔE sideband region was performed. The systematic uncertainty on the combinatorial background has been taken as 50% of the difference between the number of events obtained from the default fit and from the second fit. For the cross-feed component to the peaking background, the uncertainty of the corresponding branching fractions, taken from Ref. [10], has been assigned as the systematic error. For the contribution coming from other B decays with a J/ψ or a $\psi(2S)$ in the final state, a 50% error has been assigned, accounting for the poor knowledge of the branching fractions of the contributing decay modes. Overall, the dominant contribution to the systematic error is from the secondary-decay branching fractions in the case of $\psi(2S)\ K^{(*)}$ and $\chi_{c1}\ K$, the efficiency determination in the case of $J/\psi\ K^{(*)}$, and the background subtraction in the case of $\chi_{c1}\ K^*$.

Assuming isospin invariance in the $B \to$ charmonium K (K^*) decays, we compute $R^{+/0}$, the ratio $\Gamma(\Upsilon(4S) \to B^+B^-)/\Gamma(\Upsilon(4S) \to B^0\overline{B}^0)$. Using the ratio of the charged to neutral B meson lifetimes $\tau_{B^+}/\tau_{B^0} = 1.086 \pm 0.017$ [10], we obtain

$$R^{+/0} \equiv \frac{\Gamma(\Upsilon(4S) \to B^+B^-)}{\Gamma(\Upsilon(4S) \to B^0\overline{B}^0)} = 1.06 \pm 0.02 \pm 0.03, \qquad (2)$$

where the first error is statistical and the second systematic. The branching fractions have been determined using $R^{+/0} = 1$; they are summarized in Table II. The ratios of the branching fractions for $B \to (c\bar{c})K^*$ and $B \to (c\bar{c})K$ for the three $(c\bar{c})$ states are presented in Table III. For each of the charmonium states, the average of the charged and neutral measurements is also shown.

TABLE II. Measured branching fractions for exclusive decays of B mesons to charmonium and kaon final states. The first error is statistical and the second systematic.

Channel	Branching fraction ($\times 10^{-4}$)
$B^0 \to J/\psi\ K^{*0}$	13.09 ± 0.26 ± 0.77
$B^+ \to J/\psi\ K^{*+}$	14.54 ± 0.47 ± 0.97
$B^+ \to J/\psi\ K^+$	10.61 ± 0.15 ± 0.48
$B^0 \to J/\psi\ K^0$	8.69 ± 0.22 ± 0.30
$B^0 \to \psi(2S)\ K^{*0}$	6.49 ± 0.59 ± 0.97
$B^+ \to \psi(2S)\ K^{*+}$	5.92 ± 0.85 ± 0.89
$B^+ \to \psi(2S)\ K^+$	6.17 ± 0.32 ± 0.44
$B^0 \to \psi(2S)\ K^0$	6.46 ± 0.65 ± 0.51
$B^0 \to \chi_{c1}\ K^{*0}$	3.27 ± 0.42 ± 0.64
$B^+ \to \chi_{c1}\ K^{*+}$	2.94 ± 0.95 ± 0.98
$B^+ \to \chi_{c1}\ K^+$	5.79 ± 0.26 ± 0.65
$B^0 \to \chi_{c1}\ K^0$	4.53 ± 0.41 ± 0.51

Finally, we have measured the charge asymmetries

$$A \equiv \frac{\mathcal{B}(B^+ \to (c\bar{c})K^{+(*)}) - \mathcal{B}(B^- \to (c\bar{c})K^{-(*)})}{\mathcal{B}(B^+ \to (c\bar{c})K^{+(*)}) + \mathcal{B}(B^- \to (c\bar{c})K^{-(*)})}, \qquad (3)$$

using efficiencies determined separately for the two charges. The results are presented in Table IV. No statistically significant asymmetry is observed.

In summary, branching fraction measurements of exclusive B decays to charmonium [J/ψ, $\psi(2S)$, and χ_{c1}] and K

TABLE III. Results for ratios of the branching fractions for charmonium and a K^* versus charmonium and a K. The first error is statistical and the second systematic.

Ratio	Result
$\mathcal{B}(B^0 \to J/\psi K^{*0})/\mathcal{B}(B^0 \to J/\psi K^0)$	1.51 ± 0.05 ± 0.08
$\mathcal{B}(B^+ \to J/\psi K^{*+})/\mathcal{B}(B^+ \to J/\psi K^+)$	1.37 ± 0.05 ± 0.08
$\mathcal{B}(B \to J/\psi K^*)/\mathcal{B}(B \to J/\psi K)$	1.44 ± 0.04 ± 0.06
$\mathcal{B}(B^0 \to \psi(2S)K^{*0})/\mathcal{B}(B^0 \to \psi(2S)K^0)$	1.00 ± 0.14 ± 0.09
$\mathcal{B}(B^+ \to \psi(2S)K^{*+})/\mathcal{B}(B^+ \to \psi(2S)K^+)$	0.96 ± 0.15 ± 0.09
$\mathcal{B}(B \to \psi(2S)K^*)/\mathcal{B}(B \to \psi(2S)K)$	0.98 ± 0.10 ± 0.07
$\mathcal{B}(B^0 \to \chi_{c1}K^{*0})/\mathcal{B}(B^0 \to \chi_{c1}K^0)$	0.72 ± 0.11 ± 0.12
$\mathcal{B}(B^+ \to \chi_{c1}K^{*+})/\mathcal{B}(B^+ \to \chi_{c1}K^+)$	0.51 ± 0.17 ± 0.16
$\mathcal{B}(B \to \chi_{c1}K^*)/\mathcal{B}(B \to \chi_{c1}K)$	0.65 ± 0.09 ± 0.10

TABLE IV. Results for charge asymmetries. The first error is statistical and the second systematic.

Final state	Asymmetry
$J/\psi\ K^+$	$-0.030 \pm 0.014 \pm 0.010$
$J/\psi\ K^{*+}$	$0.048 \pm 0.029 \pm 0.016$
$\psi(2S)\ K^+$	$0.052 \pm 0.059 \pm 0.020$
$\psi(2S)\ K^{*+}$	$-0.077 \pm 0.207 \pm 0.051$
$\chi_{c1}\ K^+$	$0.003 \pm 0.076 \pm 0.017$
$\chi_{c1}\ K^{*+}$	$-0.471 \pm 0.378 \pm 0.268$

or K^* have been presented. Our results for J/ψ and $\psi(2S)$ are in good agreement with previous measurements [10] and exhibit comparable or superior precision. Our χ_{c1} results have much better precision than earlier measurements. The $B^+ \rightarrow \chi_{c1}\ K^{*+}$ mode was previously unmeasured. Assuming isospin invariance, we find the ratio of charged- to neutral-B meson production on the $\Upsilon(4S)$ resonance to be compatible with unity within 1.7 standard deviations. No direct CP violation has been observed in the charge asymmetries.

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