CLNS 00-1680
CLEO 00-12

Study of B Decays to Charmonium States $B \to \eta_c K$ and $B \to \chi_{c0} K$

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(July 6, 2000)

Abstract

In a sample of $9.66 \times 10^6 B\bar{B}$ pairs collected with the CLEO detector we make the first observation of B decays to an η_c and a kaon. We measure branching fractions $\mathcal{B}(B^+ \to \eta_c K^+) = (0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20) \times 10^{-3}$ and $\mathcal{B}(B^\circ \to \eta_c K^\circ) = (1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31) \times 10^{-3}$, where the first error is statistical, the second is systematic and the third is from the η_c branching fraction uncertainty. From these we extract the η_c decay constant in the factorization approximation, $f_{\eta_c} = 335 \pm 75$ MeV. We also search for B decays to a χ_{c0} and a kaon. No evidence for a signal is found and we set 90% CL upper limits: $\mathcal{B}(B^+ \to \chi_{c0} K^+) < 4.8 \times 10^{-4}$ and $\mathcal{B}(B^\circ \to \chi_{c0} K^\circ) < 5.0 \times 10^{-4}$.

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Two-body B decays to a charmonium state and a kaon have recently received substantial attention because of their importance for studies of CP violation in determining the angles of the CKM unitarity triangles and because of the observation of the unexpectedly large B decay rate to $\eta' X$ [1]. Among several theoretical explanations for the latter, a substantial intrinsic charm component of the η' has been proposed [2,3]. If this is the case, the η' can be produced by the axial part of the $b \to c\bar{c}s(d)$ process, which also produces the η_c. Exclusive B decays to charmonium states are also of theoretical interest as a testing ground for the QCD calculations of quark dynamics and factorization. In the absence of enhancing mechanisms, the B decay rate to $\eta_c X$ is expected to be comparable to that for the B decay to $J/\psi X$ [4–8]. Experimentally, little is known about η_c production in B decays. The only published result is from a 1995 CLEO study [11], which used 2.02 fb^{-1} of data collected at $\Upsilon(4S)$ and obtained an upper limit on inclusive η_c production: $\mathcal{B}(B \to \eta_c X) < 0.9\%$ at 90% CL.

The color-singlet production of χ_{c0} in B decays vanishes in the factorization approximation as a consequence of spin-parity conservation. However, the color-octet mechanism [9,10] allows for the production of the χ_{c0} P-wave 0^{++} state via the emission of a soft gluon. No information on B decays to χ_{c0} is available at present [13].

In this Letter we report results from the analysis of 9.13 fb^{-1} of e^+e^- annihilation data collected with the CLEO detector at the Cornell Electron Storage Ring (CESR), taken at the $\Upsilon(4S)$ energy, corresponding to 9.66×10^6 produced $B\bar{B}$ pairs. In addition, 4.35 fb^{-1} of integrated luminosity were taken 60 MeV below the $\Upsilon(4S)$ resonance in order to study backgrounds from light quark production (referred to as continuum).

The data were taken with two configurations of the CLEO detector, called CLEO II and CLEO II.V. In the CLEO II configuration of the detector [14], charged particle tracking is provided by three cylindrical drift chambers immersed in axial solenoidal magnetic field of 1.5 T. Charged particle identification (PID) is made possible by a time-of-flight system (TOF) outside of the outermost tracking chamber and by the measurement of specific ionization loss (dE/dX) in the tracking system. Photon and electron identification is provided by a high resolution electromagnetic CsI (Tl) calorimeter. The muon system is the outermost subdetector consisting of three superlayers of wire counters interspersed with steel at different absorption lengths. The CLEO II.V configuration differs from the CLEO II configuration in that the innermost drift chamber was replaced by a three layer double-sided silicon vertex detector [15] and that a helium-propane gas mixture, instead of argon-ethane, was used in the main drift chamber. These changes led to improved momentum and dE/dX resolution.

We reconstruct the η_c in the decay modes $\eta_c \to \phi\phi \to K^+K^-K^+K^-$ and $\eta_c \to K^\circ_S K^\pm \pi^\mp$ [1]. The χ_{c0} is searched for in its decay modes $\chi_{c0} \to K^+K^-$ and $\chi_{c0} \to \pi^+\pi^-$. For calculation of efficiencies, we use the branching fractions $\mathcal{B}(\chi_{c0} \to K^+K^-) = (0.586 \pm 0.086)\%$ and $\mathcal{B}(\chi_{c0} \to \pi^+\pi^-) = (0.496 \pm 0.066)\%$ obtained by averaging the PDG values [13] with the recent BES results [16]. The detector simulation is based upon GEANT 3 [17].

Candidate primary tracks must be well measured and come from the event vertex. Neutral kaons are identified as a $\pi^+\pi^-$ pair coming from a displaced vertex. The mass resolution is

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[1]Charge conjugation is implied throughout this Letter.

3.6 MeV and we select events within 8 MeV of the K_S° mass [13]. A phi meson candidate is selected as a K^+K^- pair in the mass window $1.00 < M(K^+K^-) < 1.04$ GeV.

We reconstruct the B mesons by combining an η_c or a χ_{c0} with a charged or neutral kaon. The candidate events are identified by using the difference between the reconstructed and beam energies, $\Delta E = E(B) - E_{beam}$, and the beam constrained mass, $M(B) = \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$. The resolution of ΔE is about 17 (15) MeV for CLEO II (CLEO II.V). The uncertainty in $M(B)$ is about 2.6 MeV and is dominated by the beam energy spread. Events for which multiple combinations pass the selection criteria are assigned a weight equal to the inverse of the number of candidates passing the selection. The average number of candidates per event is about 1.3 for decays in the $\eta_c \to K_S^\circ K^\pm \pi^\mp$ submode and is less than 1.1 for all other channels.

To minimize the combinatorial background coming from other B decays and from continuum production we impose PID criteria. For the $\eta_c \to \phi\phi$ submode we require that the charged kaons have dE/dX and TOF measurements within 3 standard deviations (σ) of the expected values, when such measurements are present. The $\eta_c \to K_S^\circ K^\pm \pi^\mp$ submode has more background and the PID consistency requirements in this case are at a more stringent level of 2σ, and at least one of the PID measurements has to be present for the charged kaon candidates. The secondary tracks from the χ_{c0} decay have momenta between 1.0 and 2.7 GeV, where there is little PID separation between kaons and pions, therefore, no PID requirements are imposed.

Most of the background comes from continuum production, which at CLEO has jet-like characteristics. We minimize this background by employing the ratio $R2$ of the second and zeroth Fox-Wolfram moments [18]. For isotropic events, $R2$ is nearly zero and for jet-like events it is close to one. We select events with $R2 < 0.25$ for decays with η_c and $R2 < 0.3$ for decays with χ_{c0}. In addition, we impose a lepton veto on the bachelor kaon candidate to remove possible contamination due to B semileptonic decays.

We extract the signal yield by using an unbinned extended maximum likelihood fit method described in Ref. [19]. For the $B \to \eta_c K$ analysis, the fit variables are the beam constrained mass $M(B)$, the energy difference ΔE, the η_c candidate mass and the cosine of the angle between the direction of the B candidate and the beam axis $\cos(\theta_B)$. For the $\eta_c \to \phi\phi$ mode we also use the angle χ between the planes formed by the kaons from the ϕ decays in the η_c rest frame [20].

The signal $M(B)$ and ΔE probability density functions (PDFs) are parameterized by a Gaussian and a sum of two Gaussians with the same mean, respectively. The η_c mass is represented by a Breit-Wigner function convolved with a sum of two Gaussians with the same mean. We use $13.2^{+3.8}_{-3.2}$ MeV for the η_c width [13]. The signal shape is expected to vary as $\sin^2(\theta_B)$ and $\sin^2(\chi)$. The background shape is represented by an end-point function (the product of a 2nd degree polynomial in $\sqrt{1 - (M(B)/E)^2}$ and a phase-space factor) in $M(B)$ and is linear or constant in all other fit variables. The parameters of the PDF shapes are extracted from the Monte Carlo simulation of the signal and backgrounds. We combine the yields from different data sets and from different η_c submodes by adding the log-likelihood functions. The yields and efficiencies are given in Table I.

Systematic uncertainties from the modeling of the PDF shapes are included in the fit result by varying the shape parameters according to their covariance matrices and repeating

TABLE I. Reconstruction efficiencies, including $\mathcal{B}(K^\circ \to K^\circ_S \to \pi^+\pi^-)$, and signal yields for channels with η_c.

Channel	Efficiency (%)	Fit yield (events)
$B^+ \to \eta_c K^+, \eta_c \to K^\circ K\pi$	13.0	$18.1^{+6.2}_{-5.4}$
$B^+ \to \eta_c K^+, \eta_c \to \phi\phi$	22.0	$1.4^{+1.7}_{-1.0}$
$B^\circ \to \eta_c K^\circ, \eta_c \to K^\circ K\pi$	3.9	$7.5^{+4.1}_{-3.2}$
$B^\circ \to \eta_c K^\circ, \eta_c \to \phi\phi$	6.2	$1.0^{+1.4}_{-0.7}$

the fit procedure. Systematic errors due to uncertainty in the reconstruction efficiency are quoted separately. An additional source of uncertainty is the η_c branching fractions; $\mathcal{B}(\eta_c \to K^\circ K\pi)$ has a relative error of 30.9% and $\mathcal{B}(\eta_c \to \phi\phi)$ has a relative error of 39.4%. Since the measurements of these branching fractions were made by experiments running at the J/ψ mass, they have a common error of 28.3% due to the uncertainty of the branching fraction $\mathcal{B}(J/\psi \to \gamma\eta_c)$. We quote this common error on the combined result as coming from the η_c branching fraction uncertainty. The remaining errors of 12.4% and 27.4% are included by smearing the likelihood functions for different sub-modes before they are combined.

Assuming equal production of charged and neutral B mesons in $\Upsilon(4S)$ decay, the branching fractions are $\mathcal{B}(B^+ \to \eta_c K^+) = (0.69^{+0.26}_{-0.21} \pm 0.08 \pm 0.20) \times 10^{-3}$ and $\mathcal{B}(B^\circ \to \eta_c K^\circ) = (1.09^{+0.55}_{-0.42} \pm 0.12 \pm 0.31) \times 10^{-3}$, where the first error is statistical, the second error is from the uncertainty on the reconstruction efficiency and the third error is due to the uncertainty of $\mathcal{B}(J/\psi \to \gamma\eta_c)$. The statistical significances, with PDF shape uncertainties included, are 5.2 standard deviations for the charged B decay and 4.8 for the neutral channel [12]. The confidence level of the fits are 54% and 76% for the charged and neutral decay modes, respectively. The combined $M(B)$ projections and the log-likelihood functions of the branching fractions are shown in Fig. 1.

As a cross-check we have done a counting analysis using more stringent selection criteria $|M(B) - 5.280| < 0.007$ GeV, $|\Delta E| < 0.040$ GeV and $|M(\eta_c) - 2.9798| < 0.025$ GeV. The results are statistically consistent with those stated above. We have checked the sensitivity of our result to the large spread of the η_c width measurements [13] by repeating the analysis using values of 10 and 24 MeV for the η_c width. The central values of the branching fractions are 0.64×10^{-3} and 0.78×10^{-3} for the charged decay and 1.02×10^{-3} and 1.30×10^{-3} for the neutral decay, correspondingly.

The branching fraction for the decay $B \to \eta_c K$ can be related to that of $B \to J/\psi K$ [13] in the factorization approximation by taking into account the phase space difference and hadronic current dynamics [4–8]. The ratio of decay rates is proportional to the ratio of the decay constants squared: $\Gamma(B \to \eta_c K)/\Gamma(B \to J/\psi K) = D(f_{\eta_c}/f_{J/\psi})^2$, where the coefficient D expresses the evaluation of the decay dynamics. We calculate the ratio of the decay constants from the measured branching fractions using weighted averages of charged and neutral modes and the theoretical estimates of D. Our results are consistent with the phenomenological expectations given in Table II. Using the J/ψ decay constant evaluated from dilepton rates, $f_{J/\psi} = 405 \pm 14$ MeV [21], and predictions of D by Ahmady and Mendel [5], we obtain $f_{\eta_c} = 335 \pm 52 \pm 47 \pm 12 \pm 25$ MeV, where the first error is due to the statistical and systematic errors on the exclusive branching fractions, the second error is due to the η_c branching fractions, the third error reflects the uncertainty in the J/ψ decay constant, $f_{J/\psi}$, and the last error is due to D.

TABLE II. Theoretical estimates of $\Gamma(B \to \eta_c K)/\Gamma(B \to J/\psi K)$. The first, second and fourth columns give phenomenological evaluations of different quantities. The third column lists our estimate of the decay constant ratio for a given model, where the first error originates from the branching fraction uncertainties and the second is due to the quoted error in D.

D	$f_{\eta_c}/f_{J/\psi}$	$f_{\eta_c}/f_{J/\psi}$ (exp.)	$\frac{\Gamma(B\to\eta_c K)}{\Gamma(B\to J/\psi K)}$	Ref.
$\cong 2.68$	0.78 ± 0.13	$0.54 \pm 0.10 \pm 0.00$	1.64 ± 0.27	[4]
1.12 ± 0.17	1.20 ± 0.04	$0.83 \pm 0.17 \pm 0.06$	1.6 ± 0.2	[5]
1.11 ± 0.15	0.99	$0.84 \pm 0.17 \pm 0.06$	$[0.94, 1.24]$	[6]
1.11 ± 0.15	1.03 ± 0.07	$0.84 \pm 0.17 \pm 0.06$	1.14 ± 0.17	[7]
1.43 ± 0.29	0.81 ± 0.05	$0.73 \pm 0.16 \pm 0.09$	0.94 ± 0.25	[8]

To search for the decay $B \to \chi_{c0} K$ we follow the same procedure as described above. Part of the background comes from B decays to J/ψ or D mesons, such as $B \to D\pi, D \to K\pi$. In these cases the reconstructed B momentum is close to that of the signal and the background peaks in $M(B)$. About one half of such background is removed by vetoing leptons and $K\pi$ combinations in the vicinity of charged and neutral D mesons masses. We do not model the behavior of the remaining background. Instead, we make a ± 7 MeV cut on $M(B)$. Only the ΔE and $M(\chi_{c0})$ variables are used to extract the signal. Mistaking pions from χ_{c0} decay as kaons shifts the B energy upwards by 120 MeV. The ΔE region is made asymmetric to keep event samples from different χ_{c0} decay channels from overlapping ($-150 < \Delta E < 60$ MeV for the $\chi_{c0} \to K^+K^-$ submode and $-60 < \Delta E < 150$ MeV for the $\chi_{c0} \to \pi^+\pi^-$ submode). In spite of the lepton veto some of the background due to $\psi \to \mu^+\mu^-$ decays remains in the sample because of restricted muon system acceptance. This background contributes to the $M(\chi_{c0})$ sideband of $\chi_{c0} \to K^+K^-$ submode, hence we restrict the signal plane to $M(\chi_{c0}) > 3.28$ GeV. We remove any possible contribution from $\chi_{c2} \to \pi^+\pi^-$ or K^+K^- by imposing a skew veto cut $\Delta E > M(\chi_{c0}) - 3.5$ GeV.

The final results were extracted from the limited region of ΔE and $M(\chi_{c0})$. The same unbinned maximum likelihood procedure was used as for the $B \to \eta_c K$ analysis. The observed yields are not statistically significant and the resulting 90% confidence level upper limits are 0.48×10^{-3} and 0.50×10^{-3} for the charged and neutral modes, respectively [22].

In summary, we have observed the decay $B \to \eta_c K$ in both charged and neutral modes with branching fractions similar to those for $B \to J/\psi K$. By comparing the rates of the decays with η_c and J/ψ, we have extracted the η_c decay constant. The channel $B^\circ \to \eta_c K^\circ$ can be used to extract the value of $\sin(2\beta)$ via measurement of time-dependent asymmetry.

We have also set upper limits on $B \to \chi_{c0} K$ decays that restricts a possible enhancement of the χ_{c0} production due to the color octet mechanism.

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, the Texas Advanced Research Program, and the Alexander von Humboldt Stiftung.

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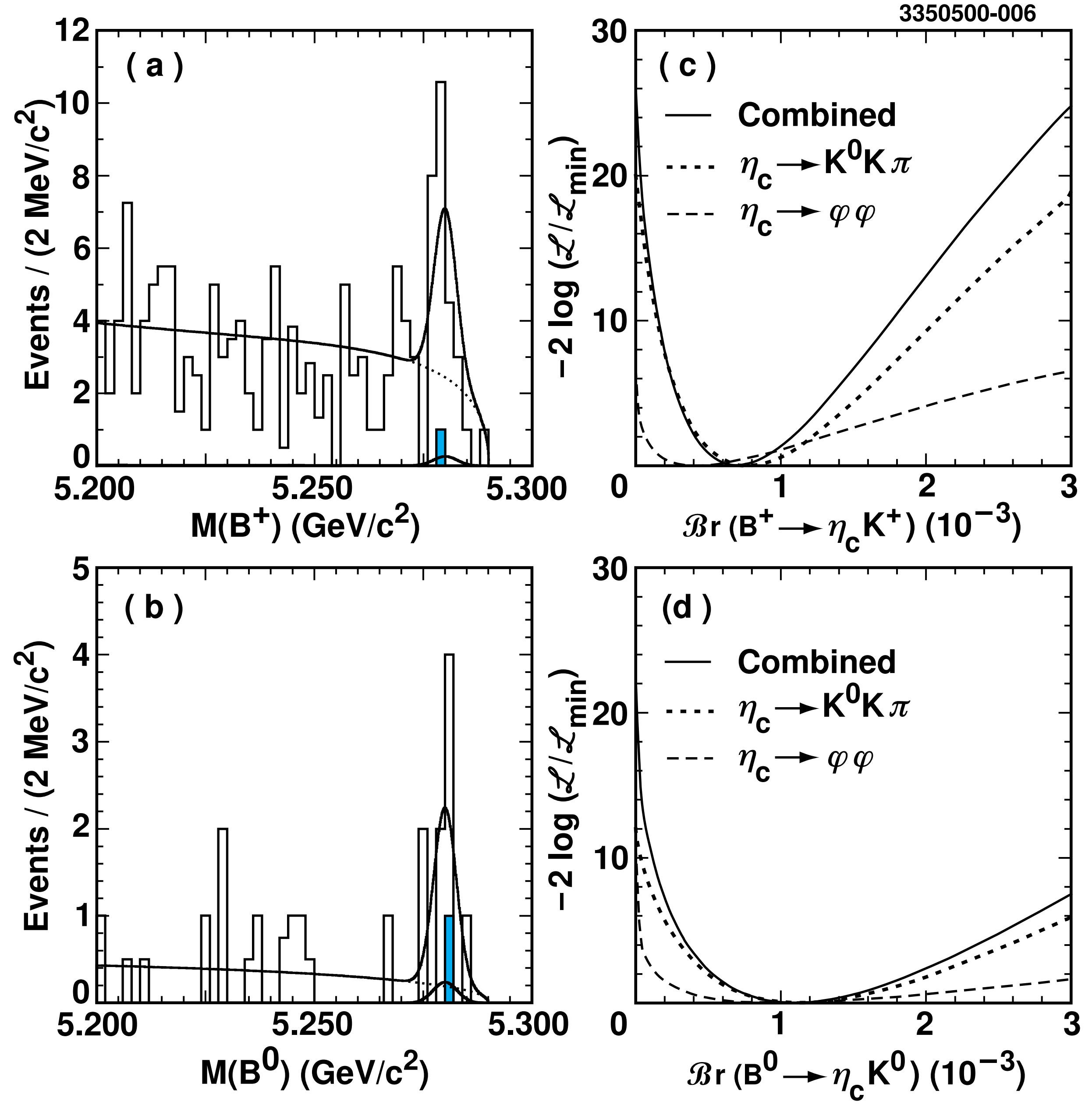

FIG. 1. Beam constrained mass spectra and the log-likelihood functions for charged (a and c) and neutral (b and d) B decay channels. The mass spectra include both η_c channels combined, with $\eta_c \to \phi\phi$ also shown separately as the shaded area. The solid line in figures (a) and (b) displays the signal plus background combined shape. The dashed line corresponds to the background shape only. A cut on the signal likelihood using all variables except $M(B)$ is used to make these projections.