DECAYS OF THE B MESON INVOLVING CHARMONIUM

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ABSTRACT

We have used the CLEO-II detector at the Cornell Electron Storage Ring to measure the branching fractions for B-meson decays into charmonium mesons (J/ψ, ψ', χ_{c1}, χ_{c2} and η_c) in a sample of 2.15 million $B\overline{B}$ events. Momentum spectra for inclusive J/ψ and ψ' production are presented. We also find an exclusive branching fraction for the Cabibbo suppressed decay $B\to J/\psi\pi^-$.

1. Introduction

Inclusive decays of B mesons to charmonium states provide a testing ground for QCD calculations of quark dynamics. The dominant mechanism for production of charmonium is the color-suppressed internal spectator diagram. Virtual gluon interactions complicate this picture.[1,2] These are difficult to handle in QCD, and alternative approaches[3,4] result in significantly different predictions.

The data used in this analysis were recorded with the CLEO-II detector. An integrated luminosity of 2.02 fb^{-1} was accumulated at the $\Upsilon(4S)$ resonance, and an additional 0.99 fb^{-1} was collected at energies just below that resonance. Only the first half of this sample was used to study $B\to J/\psi X$, for which systematic effects were the primary limitation. With event selection optimized for B decays to charmonium we found $(2.15 \pm 0.04) \times 10^6$ $B\overline{B}$ events.

The CLEO-II detector[5] consists of three concentric cylindrical wire drift chambers, a time-of-flight system, and an electromagnetic calorimeter of 7800 thallium-doped cesium iodide crystals. Outside the calorimeter are a 1.5-Tesla superconducting solenoidal magnet and muon detectors embedded in steel.

2. $B\to J/\psi$X

We reconstructed J/ψ's through their decays to e^+e^- and $\mu^+\mu^-$. The invariant mass distributions for dielectrons and dimuons are shown in Fig. 1. The signal shapes were derived from a Monte Carlo simulation of $B\to J/\psi X$, $J/\psi\to e^+e^-$ or $\mu^+\mu^-$, that included bremsstrahlung in the detector material and final-state radiation. Continuum background was determined with the below $\Upsilon(4S)$ data. Fig. 2 shows the continuum dilepton mass spectra for momenta below 2.0 GeV/c. Using the MARK-III[6] branching fractions, $\mathcal{B}(J/\psi\to e^+e^-)$=(5.92$\pm$0.25)%, and $\mathcal{B}(J/\psi\to\mu^+\mu^-)$=(5.90$\pm$0.25)%, we find $\mathcal{B}(B\to J/\psi X)$=(1.14$\pm$0.06)% using dielectrons and $\mathcal{B}(B\to J/\psi X)$=(1.13$\pm$0.05)% using dimuons, where the errors are statistical only. There are significant systematic uncertainties, principally in lepton identification and the J/ψ to dilepton branching fractions. Combining the two modes, we find $\mathcal{B}(B\to J/\psi X)$=(1.13$\pm$0.04$\pm$0.06)%.

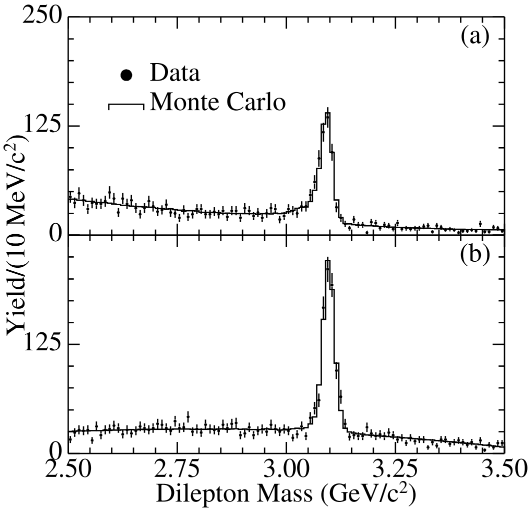


Fig. 1. Mass distributions for (a) dielectron and (b) dimuon modes from B decays.

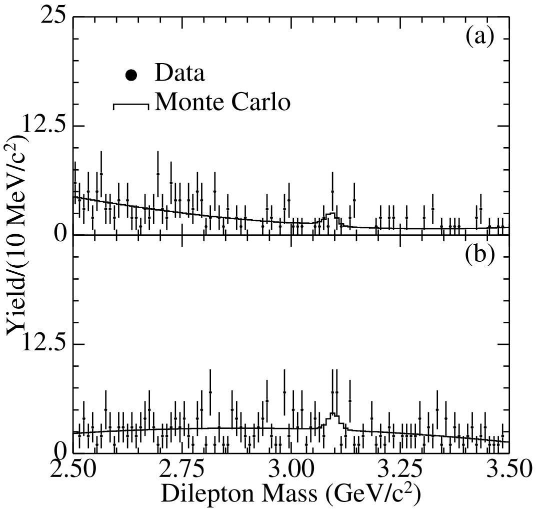


Fig. 2. Mass distributions from continuum data for (a) dielectrons and (b) dimuons, with P_{l+l-}<2 GeV/c and Fox-Wolfram R_2<0.5.

3. $B \rightarrow \psi' \mathrm{X}$

We measured B-meson decays to ψ' using two decay channels, $\psi' \rightarrow \ell^+\ell^-$ and $\psi' \rightarrow J/\psi\pi^+\pi^-$. The distribution of dilepton invariant masses in the ψ' region is shown in Fig. 3. The distribution of the difference between the masses of reconstructed ψ' and J/ψ candidates for $\psi' \rightarrow J/\psi\pi^+\pi^-$ is shown in Fig. 4. Using the mass difference reduces the effect of the error in the J/ψ mass measurement. We find the $B \rightarrow \psi'$X branching fraction for the modes $\psi' \rightarrow \ell^+\ell^-$and $\psi' \rightarrow J/\psi\pi^+\pi^-$ to be $(0.30 \pm 0.05 \pm 0.04)\%$ and $(0.38 \pm 0.05 \pm 0.05)\%$, respectively. Since the samples are statistically independent they can be combined into a single result: $(0.34 \pm 0.04 \pm 0.03)\%$.

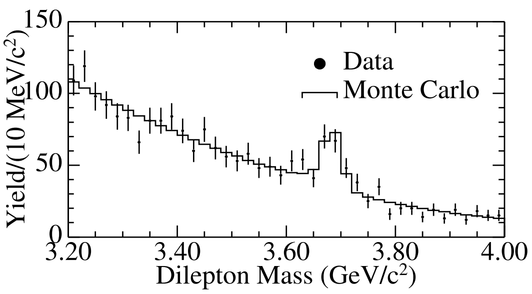


Fig. 3. Dilepton mass distribution.

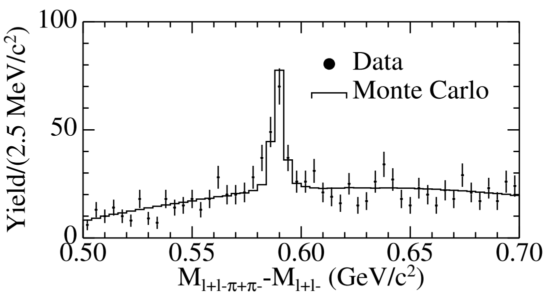


Fig. 4. Distribution of the difference between the $\ell^+\ell^-\pi^+\pi^-$ and $\ell^+\ell^-$ masses.

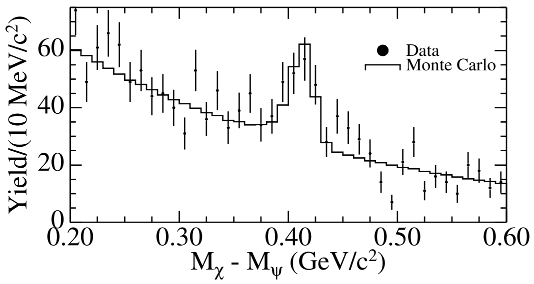


Fig. 5. Mass-difference distribution for $J/\psi\gamma$; fit to $B\rightarrow\chi_{c1}$X Monte Carlo.

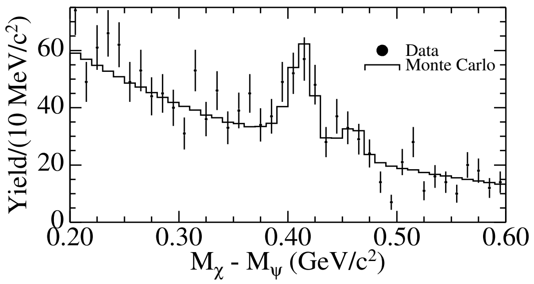


Fig. 6. Mass-difference distribution for $J/\psi\gamma$; fit to $B\rightarrow\chi_{c1}$X and $B\rightarrow\chi_{c2}$X Monte Carlo.

4. $B\rightarrow\chi_c$X

Inclusive χ_c events were reconstructed by combining detected photons with any accompanying J/ψ candidates. The largest background is random combinations of photons from π^0's with real J/ψ's from B-meson decays. Any candidate photon which could be combined with another photon to produce an effective mass near the π^0 mass was rejected. Fig. 5 shows a fit to the resulting mass-difference distribution with only the χ_{c1} allowed, which gives a signal of 112$\pm$17 events. A better fit is obtained by allowing for both χ_{c1} and χ_{c2} (Fig. 6). The χ_{c1} signal is unchanged while there are 35$\pm$13 entries in the χ_{c2} region. We find $\mathcal{B}(B\rightarrow\chi_{c1}\mathrm{X})=(0.40\pm0.06\pm0.04)\%$. The marginal excess in the χ_{c2} region corresponds to $\mathcal{B}(B\rightarrow\chi_{c2}\mathrm{X})=(0.25\pm0.10\pm0.03)\%$, or a 90% confidence lever upper limit of 0.38%.

5. $B\rightarrow\eta_c$X

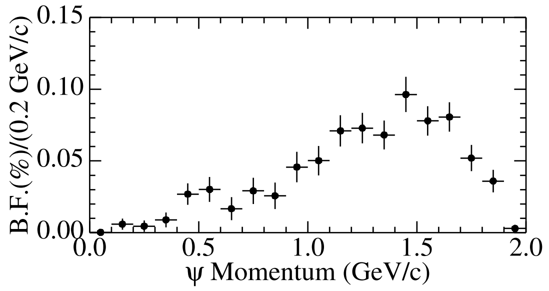
We searched for the decay $\eta_c \rightarrow \phi\phi$, $\phi \rightarrow K^+K^-$. The signal region was defined to be the interval 2960 to 3010 MeV, allowing for the uncertainty in the η_c mass.[7,8] The dominant systematic error is the 40% uncertainty in $\mathcal{B}(\eta_c \rightarrow \phi\phi)$. We derive an upper limit on the branching ratio $\mathcal{B}(B \rightarrow \eta_c\mathrm{X}) < 1.0\%$ at 90% confidence level.

6. Momentum Spectra of J/ψ and ψ' From B Decay

The J/ψ momentum spectrum is shown in Fig. 7 with the expected contributions from the feed-down modes $B\rightarrow\psi'$X and $B\rightarrow\chi_c$X subtracted. The momentum spectrum of the ψ''s is shown in Fig. 8. In both cases, the observed shapes include soft components attributable to $B\rightarrow J/\psi(\psi')$ X with higher K* resonances or multiple hadrons.

7. The Exclusive Decay $B\rightarrow J/\psi\pi$

We combine π^- candidates with detected J/ψ's to reconstruct the B meson. Figure 9 shows the energy difference (ΔE) between the B and beam energies, plotted against the reconstructed B mass, where the beam energy has been substituted for the reconstructed energy. The background is dominated by $B^-\rightarrow J/\psi\mathrm{K}^-$, where the K$^-$ is misidentified as a pion (Fig. 10). We find $\mathcal{B}(B^-\rightarrow J/\psi\pi^-)=(1.10\pm0.15\pm0.09)\times10^{-3}$, in agreement with expectations relative to $B^-\rightarrow J/\psi\mathrm{K}^-$ for a Cabibbo suppressed decay. We also find $\mathcal{B}(\overline{B}^0\rightarrow J/\psi\pi^0)<6.9\times10^{-5}$ at 90% confidence limit.



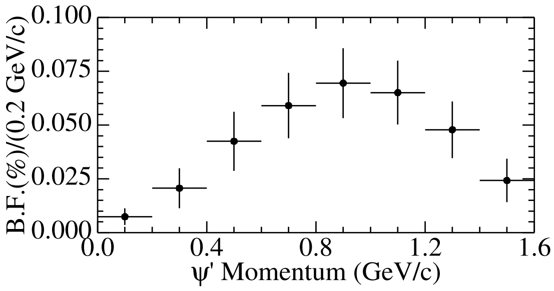
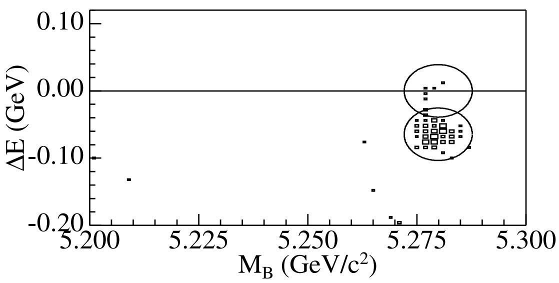


Fig. 7. Momentum spectrum for direct inclusive J/ψ production from B decays, see text.

Fig. 8. Momentum spectrum for inclusive ψ' production from B decays.



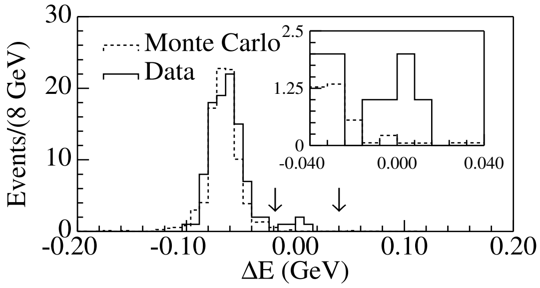


Fig. 9. Correlation between ΔE and M_B in the expected $B^-\to J/\psi\pi^-$ signal region. The ellipses show the 3 standard deviation contours expected for $B\to J/\psi\pi^-$ and $B\to J/\psi\mathrm{K}^-$.

Fig. 10. The ΔE projection for events with reconstructed mass within 3σ of the B mass. The arrows point to the $B\to J/\psi\pi^-$ signal region.

8. Summary of Results and Comparison to Theory

Table 1 summarizes our inclusive measurements with the corresponding Particle Data Group (PDG) values. (The PDG values for $B\to J/\psi\mathrm{X}$ and $B\to\psi'\mathrm{X}$ have been corrected to use the Mark III $J/\psi\to\ell^+\ell^-$ branching fractions.) The measured branching fraction for $B\to J/\psi\mathrm{X}$ and $B\to\chi_c\mathrm{X}$ are composed of "direct" production, and "feed down" from charmonium modes, such as $B\to\psi'\mathrm{X}$, $\psi'\to J/\psi\pi^+\pi^-$or $\psi'\to\chi_{c1}\gamma$. To obtain the direct rate for comparison with theoretical predictions, we correct the inclusive branching fraction for the feed-down component. The direct branching fractions for J/ψ and χ_{c1} are included in Table 1.

The interaction Hamiltonian for charmonium production in B-meson decay is

$$\mathrm{H}_{\mathit{Effective}} = \frac{G_F}{\sqrt{2}}\mathrm{V}_{cb}\mathrm{V}^*_{cs}\left[\left(\frac{1}{3}c_1(\mu)+c_2(\mu)\right)(\bar{c}c)(\bar{s}b)+\frac{1}{2}c_1(\mu)(\bar{s}\lambda_i b)(\bar{c}\lambda_i c)\right]. \qquad (1)$$

The first part of Eq. (1) transforms as a color singlet and contributes only to J/ψ, ψ', χ_{c1} and η_c production. The second part transforms as a color octet and contribute to χ_{c0}, χ_{c1}, χ_{c2} and h_c production.[4] If the $\frac{1}{3}$ (reflecting color suppression) is replaced by $1/\mathrm{N}_c$ then the coefficient of the color singlet part is equivalent to the a_2 term in the

Charmonium	Yield	Branching Fraction (%)		
		Measured	PDG (%)[7]†	Direct
η_c		<1.0		
J/ψ	1455±49	1.13±0.04±0.06	1.31±0.19	0.81±0.08
$\psi'\to\ell^+\ell^-$	127±21	0.30±0.05±0.04		
$\psi'\to J/\psi\pi^+\pi^-$	113±16	0.38±0.05±0.05		
ψ' combined		0.34±0.04±0.03	0.53±0.23	
χ_{c1}	112±17	0.40±0.06±0.04	1.05±0.35±0.25‡	0.37±0.07
χ_{c2}	35±13	<0.38		

†Corrected for recently updated $J/\psi\to\ell^+\ell^-$ branching ratios. ‡ARGUS[9]

Table 1. Inclusive $B\to$Charmonium + X. For η_c and χ_{c2} the limits are at the 90% C.L.

factorization model of Wirbel, Stech and Bauer for exclusive decays.[10] The difference between 1/N$_c$ and $\frac{1}{3}$ parameterizes non-factorizable contributions to B-meson decay.[11]

Predictions for $\mathcal{B}(B\to J/\psi X)$ range from 0.2% to 2.0%, depending on the Wilson coefficients c_1 and c_2, and 1/N$_c$.[3,4] With 1/N$_c$=3, contributions of c_1 and c_2 almost cancel in the singlet term. Following the method of Bodwin *et al.*,[4] and using the values $c_1 = 1.13$ and $c_2 = -0.29$,[11] and a b mass of 5.0 GeV/c^2, we find the prediction for $\mathcal{B}(B\to J/\psi X)$ direct to be 0.10%. If one replaces $(\frac{1}{3}c_1 + c_2)$ by the measured value of a_2 from exclusive decays (0.23±0.01±0.01[12]) then one predicts the direct branching fraction for $B\to J/\psi X$ to be 0.75%, in agreement with our measurement.

The success of using a_2 in this way prompts us to examine the predictions of Bodwin *et al.* for χ_{c2} production.[4] The difference in the predicted χ_{c1} branching fraction from the color-singlet term and our measured branching fraction gives a measure of color-octet production. Following the method of Bodwin *et al.*, but with the values of c_1, c_2 and b mass given above and using the branching fraction for χ_{c1}, we calculate $\mathcal{B}(B\to\chi_{c2}X)$=(0.56±0.15)%, larger than our measured value. They have assumed N$_c$=3, implying a small contribution from the color-singlet mode. When we replace $(\frac{1}{3}c_1 + c_2)$ by a_2, we predict $\mathcal{B}(B\to\chi_{c2}X)$=(0.30±0.11)%, in good agreement with the measured value of (0.25±0.10)% we obtain if we assume the χ_{c2} signal is real.

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