Measurements of Inclusive $B \to \psi$ Production

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Using the combined CLEO II and CLEO II.V data sets of 9.1 fb^{-1} at the $\Upsilon(4S)$, we measure properties of ψ mesons produced directly from decays of the B meson, where "B" denotes an admixture of B^+, B^-, B^0, and $\bar{B}^0$, and "ψ" denotes either $J/\psi(1S)$ or $\psi(2S)$. We report first measurements of ψ polarization in $B \to \psi(\mathrm{direct})X$: $\alpha_{\psi(1S)} = -0.30^{+0.07}_{-0.06} \pm 0.04$ and $\alpha_{\psi(2S)} = -0.45^{+0.22}_{-0.19} \pm 0.04$. We also report improved measurements of the momentum distributions of ψ produced directly from B decays, correcting for measurement smearing. Finally, we report measurements of the inclusive branching fraction for $B \to \psi X$ and $B \to \chi_{c1} X$.

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Most recent efforts to understand the production mechanism of ψ mesons have utilized the effective field theory of nonrelativistic QCD (NRQCD) [1], particularly after measurements of the prompt ψ production rate at the Tevatron [2,3] ruled out the Color Singlet Model. The relatively large production rate was better accommodated by NRQCD calculations [4]; however, measurements of the polarization of these prompt ψ [5] deviate from NRQCD calculations at high p_T. These calculations rely on a set of process-independent long-distance matrix elements (LDME's), which also appear in NRQCD calculations of ψ production in B decays. The polarization of ψ produced from B decays [6,7] is sensitive to the color-octet LDME's; however, these calculations have been done only to leading order. The momentum distribution of ψ produced in B decays [8–10] is also sensitive to the dominant color-octet terms, particularly at low p_ψ. The $\psi(1S)$ momentum distribution is also of interest as a potential indicator of an intrinsic charm component in B mesons [11]. Finally, the inclusive branching fraction $\mathcal{B}(B \to \psi X)$ [9,12,13] constrains a sum of LDME's. This Letter reports new measurements of these three properties of ψ production in B decays.

Our analysis [14] is based on 9.7×10^6 $B\overline{B}$ events ($9.1\ \text{fb}^{-1}$) produced on the $\Upsilon(4S)$ resonance. Additionally, $4.4\ \text{fb}^{-1}$ of data collected slightly below the $\Upsilon(4S)$ resonance were used to subtract the small ($\approx 2\%$) contribution of continuum ($e^+e^- \to q\overline{q}$, $q \in \{u, d, c, s\}$) $\psi(1S)$ production. The e^+e^- collisions were delivered by the Cornell Electron Storage Ring (CESR) and detected with two configurations of the CLEO detector, CLEO II [15] and CLEO II.V [16].

We select events that have spherical energy distributions and are likely to be hadronic. We reconstruct ψ candidates in the dilepton modes $\psi \to \mu^+\mu^-$ and $\psi \to e^+(\gamma)e^-(\gamma)$. The selection criteria were chosen with a goal of high detection efficiency. In the dimuon channel, at least one of the muon candidates must penetrate at least three interaction lengths into the iron of the solenoid return yoke; if only one candidate satisfies this, then the other candidate must leave a shower in the crystal calorimeter which is consistent with that of a minimum ionizing particle. In the dielectron channel, we use shower information from the crystal calorimeter and measurements of specific ionization from the drift chamber to identify electron candidates. We also attempt to recover up to one bremsstrahlung photon for each electron candidate. To do this, we select the most collinear shower within a 5° cone around the initial electron direction; furthermore, the shower must not be associated with any track, and, when combined with any other shower in the event, must not result in an invariant mass consistent with a π^0. The PDG 2001 [17] branching fractions are used to combine results from the electron and muon channels, except for $\mathcal{B}[\psi(2S) \to \mu^+\mu^-]$, which we assume by lepton universality to be equal to $\mathcal{B}[\psi(2S) \to e^+e^-]$, with an uncertainty of 20% of itself; this is consistent with recent measurements [18].

About 70% of the $\psi(1S)$ created in B decays are direct products of the B meson; the others are produced through the "feed-down" chains $B \to \psi(2S) \to \psi(1S)$ and $B \to \chi_{c1} \to \psi(1S)$ [17]. Our measurements of directly produced $\psi(1S)$ are obtained by subtracting the contributions of the feed down $\psi(1S)$ from the inclusive $\psi(1S)$ sample. We identify feed down $\psi(1S)$ by attempting to reconstruct $\chi_{c1} \to \psi(1S)\gamma$ and $\psi(2S) \to \psi(1S)\pi^+\pi^-$ for every event with a $\psi(1S)$ candidate within $^{+25}_{-50}$MeV of the nominal mass. We reconstruct $(M_{\ell^+\ell^-\pi^+\pi^-} - M_{\ell^+\ell^-})$ and $(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$, which have better resolution than the reconstructed $\psi(2S)$ and χ_{c1} invariant masses themselves. In the $\psi(2S) \to \psi(1S)\pi^+\pi^-$ decay chain, we reduce low-momentum pion background by requiring $M_{\pi^+\pi^-} > 0.45$ GeV, which has an efficiency of about 85%, from Monte Carlo simulation. This decay mode is also used to improve the statistics in our measurements of the inclusive branching fraction and the $\psi(2S)$ momentum distribution in $B \to \psi(2S)X$. We do not reconstruct the related decay $\psi(2S) \to \psi(1S)\pi^0\pi^0$, and argue that the properties of $\psi(1S)$ from this decay are identical to those of $\psi(1S)$ from $\psi(2S) \to \psi(1S)\pi^+\pi^-$; the kinematic difference in the momentum distribution is small compared to the experimental resolution, and the isospin state of the $\pi\pi$ state has no bearing on the polarization of the $\psi(1S)$.

The CLEO Monte Carlo simulation, based on GEANT [19], is used to obtain the invariant mass line shape for signal events and to estimate the detection efficiency. Simulations of the CLEO II or CLEO II.V detectors are used to generate the Monte Carlo events, such that the number of generated events for each detector is proportional to the integrated luminosity in the data. In these simulated signal events, one of the B mesons decays via one of the decay chains listed above. For each decay chain, we generate two samples of events; one with all ψ longitudinally polarized, the other with all ψ transversely polarized. We find that the detection efficiency varies slightly as a function of ψ momentum and polarization.

The procedure and results for the inclusive branching fraction and momentum distribution measurements are as follows. We divide the data into bins in p_ψ, the momentum of the ψ candidate, using a bin size of 0.1 GeV$/c$. For each bin, the invariant mass distribution of ψ candidates is fit to a sum of a signal line shape, obtained from the Monte Carlo simulation, and a cubic polynomial background. The average χ^2 of the fits is consistent with the number of degrees of freedom, thus justifying our choice of the above parametrization. We repeat this procedure using signal Monte Carlo events, binning in generated ψ momentum, to obtain detection efficiencies as a function of p_ψ. The data are then corrected for detection efficiency bin by bin; this minimizes the effect of any discrepancy between the true p_ψ distribution and that generated by the Monte Carlo simulation. Similarly, we fit the invariant mass distributions of $(M_{\ell^+\ell^-\pi^+\pi^-} - M_{\ell^+\ell^-})$ and $(M_{\ell^+\ell^-\gamma} - M_{\ell^+\ell^-})$, to extract efficiency-corrected yields of feed down $\psi(1S)$. We thus obtain momentum distributions of $\psi(1S)$ and $\psi(2S)$ which have been corrected for detection efficiency, $\psi(1S)$ feed down, and continuum background. The yields are then normalized by $n_B\mathcal{B}[\psi \to \ell^+\ell^-(\pi^+\pi^-)]$, where n_B is the number of B and $\overline{B}$ mesons in the data; the uncertainties in these quantities are reflected in our results as an overall scale factor error. Inclusive branching fractions are obtained by summing the normalized momentum distributions over all bins. Finally, the Monte Carlo simulation is used to obtain a matrix which correlates the momentum of the ψ as generated to the momentum as measured; by inverting this matrix and applying it to the observed momentum distribution, we are able to deconvolve the effects of detector measurement smearing from the distribution.

We investigate the possible sources of systematic error; for each source, we make an appropriate modification to the measurement procedure and observe the deviation of the resulting yield relative to the nominal procedure. The deviations are then combined to obtain final systematic errors. The sources of error are grouped as follows: (i) Monte Carlo simulation of track and shower finding, electron and muon identification, ψ polarization, global event, and kinematic cuts; (ii) invariant mass fit procedure; (iii) branching fractions of unmeasured modes; and (iv) overall scale factor.

The results for the inclusive branching fractions are given in Table I and the momentum distributions are shown in Fig. 1. Our branching fraction results are consistent with previous published measurements [22] as well as preliminary measurements [23] and are limited by systematic errors. The combined error for $\mathcal{B}[B \to \psi(1S)(\text{direct})X]$ is smaller than the error of the PDG 2001 average [17] by a factor of 2. However, the theoretical uncertainties in the NRQCD calculations of the branching fractions are such that the improved accuracy of this measurement is unlikely to further constrain the NRQCD LDME's. The momentum distributions reported here are the first to subtract the *measured* distributions of feed down and continuum ψ, correct for detector measurement smearing, and analyze systematic errors for each bin individually. Figure 1(b) is also the first to show the momentum distribution of multibody ($\geq$ 3-body) decays in $B \to \psi(2S)X$ production; these decays account for much of the total $B \to \psi(2S)X$ production, as is also the case with $B \to \psi(1S)X$ [9]. It should be possible to update previous phenomenological studies of the ψ momentum distribution with these improved measurements.

The polarization parameter α is equal to (+ 1, 0, −1) for a population of (transversely, randomly, longitudinally) polarized ψ. For $\psi \to \ell^+\ell^-$ decays, it is

TABLE I. Inclusive branching fraction results. The errors shown are (in order) statistical, systematic, and due to an overall scale factor uncertainty.

Decay	Branching Fraction (%)
$B \to \psi(1S)X$	$1.121 \pm 0.013 \pm 0.040 \pm 0.013$
$B \to \psi(1S)(\text{direct})X$	$0.813 \pm 0.017 \pm 0.036 \pm 0.010$
$B \to \chi_{c1}X \to \psi(1S)X$	$0.119 \pm 0.008 \pm 0.009 \pm 0.001$
$B \to \chi_{c1}X$	$0.435 \pm 0.029 \pm 0.031 \pm 0.026$
$B \to \psi(2S)X \to \psi(1S)X$	$0.189 \pm 0.010 \pm 0.018 \pm 0.002$
$B \to \psi(2S)X$	$0.316 \pm 0.014 \pm 0.023 \pm 0.016$

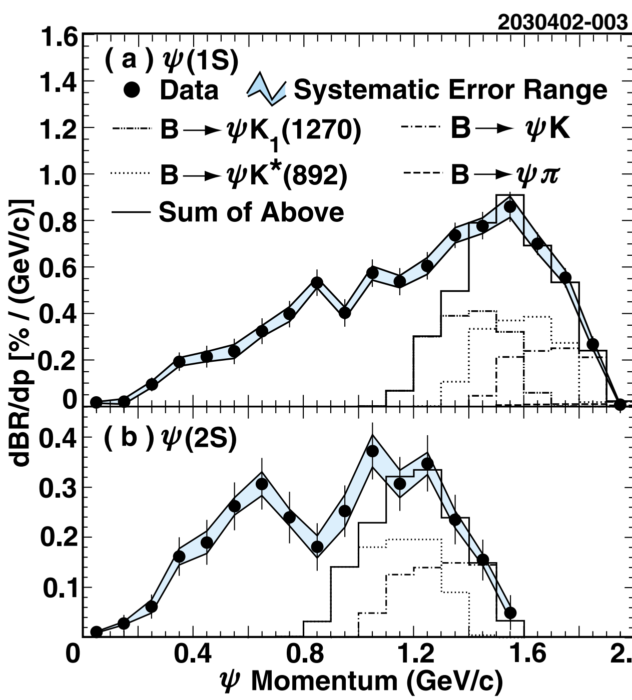

FIG. 1 (color online). Momentum distributions of (a) $\psi(1S)$ and (b) $\psi(2S)$ produced directly from B decays. There is an additional overall scale uncertainty of 1.2% for $\psi(1S)$ and 5.1% for $\psi(2S)$ which is not depicted in the plots. The shaded region shows the range over which the central values might shift as a result of systematic biases; the points show the data with 1σ statistical uncertainties. The histograms show the contributions of two-body $B \to \psi X$ decays, where the line shapes are obtained from Monte Carlo simulation and the normalizations are from previous determinations of exclusive branching fractions [17,20,21].

determined experimentally by measuring the decay angle θ, which is defined as the angle between the ℓ^+ direction in the ψ rest frame and the ψ direction in the B rest frame. The $\cos\theta$ distribution for a population of ψ is proportional to $(1 + \alpha\cos^2\theta)$. The angular distribution is obtained in a similar manner as the momentum distributions: the data set is partitioned into five equal bins in $\cos\theta$ between -1 and 1; for each partition, we fit the invariant mass distribution to find the signal yield. In addition to measuring the polarization of direct $\psi(1S)$ and $\psi(2S)$ for all momenta, we also extract $\alpha_{\psi(1S)}$ in three coarse momentum bins.

At CLEO, B mesons are produced with a small boost in the $\Upsilon(4S)$ (lab) frame, the direction of which is unknown. The boost of the B results in a smeared measurement of $\cos\theta$; directly fitting for α using the measured $\cos\theta$ distribution would yield a biased result. However, this kinematic smearing is accurately modeled by the Monte Carlo simulation. Our procedure is to generate Monte Carlo events in two sets: one with all ψ generated longitudinally, the other with all transverse. The measured $\cos\theta$ distribution from the data is then fit to a sum of the reconstructed $\cos\theta$ distributions from the polarized Monte Carlo sets. This procedure correctly accounts for both the boost smearing and detection efficiency. Since the efficiency also depends on p_ψ, we must ensure that the Monte Carlo distributions of generated p_ψ match those of Fig. 1; this is accomplished through a rejection technique.

We obtain angular distributions of $\psi(1S)$ produced directly from B decays by subtracting the angular distributions of feed down $\psi(1S)$ from that of inclusive $\psi(1S)$. However, because the observed $\cos\theta$ distributions are not directly corrected for detection efficiency, the observed feed-down distributions are corrected only for the efficiency of detecting the additional particles needed to reconstruct the $\psi(2S)$ or χ_{c1}. The final feed-down and continuum-subtracted angular distributions are shown in

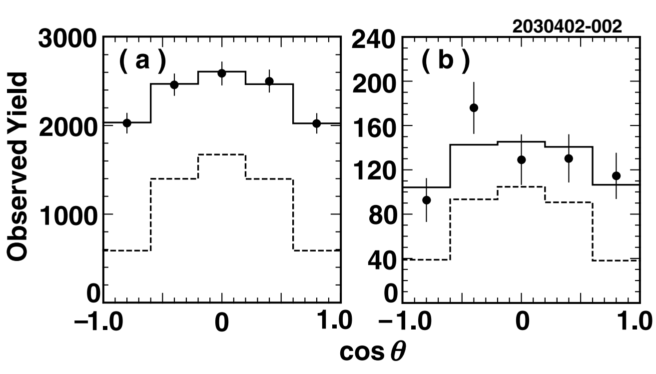

FIG. 2. Decay angle distributions of (a) $\psi(1S)$ and (b) $\psi(2S)$ from $B \to \psi(\text{direct})X$, summed over all p_ψ. The points represent the data, showing 1σ statistical uncertainties. In both figures, the fit result (solid histogram) is the sum of a longitudinal component (dashed histogram) and a transverse component.

TABLE II. Polarization of $\psi(1S)$ and $\psi(2S)$ from $B \to \psi(\text{direct})X$ over the full momentum range (top two values) and for $\psi(1S)$ in three momentum ranges. The errors are statistical and systematic.

ψ meson	p_ψ (GeV/c)	α
$\psi(1S)$	$0.0 - 2.0$	$-0.30^{+0.07}_{-0.06} \pm 0.04$
$\psi(2S)$	$0.0 - 1.6$	$-0.45^{+0.22}_{-0.19} \pm 0.04$
$\psi(1S)$	$0.0 - 0.8$	$+0.32^{+0.33}_{-0.27} \pm 0.15$
$\psi(1S)$	$0.8 - 1.4$	$-0.37^{+0.09}_{-0.09} \pm 0.04$
$\psi(1S)$	$1.4 - 2.0$	$-0.52^{+0.08}_{-0.07} \pm 0.03$

Fig. 2. The systematic error study included the previously mentioned sources of bias; additionally, we have investigated the possible systematic error arising for the methods for feed-down subtraction and fitting for α.

The final polarization results are listed in Table II; these are the first results for the polarization of $\psi(1S)$ and $\psi(2S)$ from $B \to \psi(\text{direct})X$. For comparison, we measure $\alpha = -0.35 \pm 0.03$(statistical error only) for $\psi(1S)$ from $B \to \psi(1S)(\text{all})X$. Our result for $\alpha_{\psi(1S)}$ is about 4 standard deviations from zero. This measurement therefore strongly disfavors the color evaporation model of charmonium production [24], which hypothesizes that soft gluon exchange dominates and "evaporates" the initial color-spin state of the $c\bar{c}$ system, leading to a prediction of zero net polarization, independent of the production mechanism.

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