PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 34, NUMBER 11 | 1 DECEMBER 1986

Study of the decay $B \to \psi X$

M. S. Alam, N. Katayama, I. J. Kim, C. R. Sun, and V. Tanikella
State University of New York at Albany, Albany, New York 12222

A. Bean, G. J. Bobbink, I. Brock, A. Engler, T. Ferguson, R. Kraemer,
C. Rippich, R. Sutton, and H. Vogel
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

C. Bebek, K. Berkelman, E. Blucher, D. G. Cassel, T. Copie, R. DeSalvo,
J. W. DeWire, R. Ehrlich, R. S. Galik, M. G. D. Gilchriese, B. Gittelman, S. W. Gray,
A. M. Halling, D. L. Hartill, B. K. Heltsley, S. Holzner, M. Ito, J. Kandaswamy,
R. Kowalewski, D. L. Kreinick, Y. Kubota, N. B. Mistry, J. Mueller, R. Namjoshi,
E. Nordberg, M. Ogg, D. Perticone, D. Peterson, M. Pisharody, K. Read, D. Riley,
A. Silverman, S. Stone, and Xia Yi*
Cornell University, Ithaca, New York 14853

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

P. Avery and D. Besson
University of Florida, Gainesville, Florida 32611

T. Bowcock, R. T. Giles, J. Hassard,† K. Kinoshita, F. M. Pipkin, Richard Wilson,
J. Wolinski, and D. Xiao
Harvard University, Cambridge, Massachusetts 02138

T. Gentile, P. Haas, M. Hempstead, T. Jensen, H. Kagan, and R. Kass
Ohio State University, Columbus, Ohio 43210

S. Behrends, Jan M. Guida, Joan A. Guida, F. Morrow, R. Poling, C. Rosenfeld,‡
E. H. Thorndike, and P. Tipton
University of Rochester, Rochester, New York 14627

D. Bortoletto, A. Chen, L. Garren, M. Goldberg, R. Holmes, N. Horwitz,
A. Jawahery, P. Lubrano, G. C. Moneti, and V. Sharma
Syracuse University, Syracuse, New York 13210

S. E. Csorna, M. D. Mestayer, R. S. Panvini, and G. B. Word
Vanderbilt University, Nashville, Tennessee 37235

(Received 27 June 1986; revised manuscript received 2 September 1986)

We have measured the inclusive branching ratio for $B \to \psi X$ to be $(1.09\pm0.16\pm0.21)\%$, and the exclusive branching ratios for $B^- \to \psi K^-$ and $\bar{B}^0 \to \psi \bar{K}^{*0}$ to be $(0.09\pm0.05)\%$ and $(0.41\pm0.18)\%$, respectively. The mass difference between neutral and charged B mesons is 1.1 ± 2.1 MeV, while the difference between the mass of $\Upsilon(4S)$ and twice the mean B-meson mass is 18.5 ± 3.0 MeV. The ψ momentum distribution implies a substantial two-body decay (in agreement with direct measurements), but also some combination of $B \to \psi X$ with $M_X > 1.5$ GeV, and $B \to \psi' X$.

I. INTRODUCTION

The decay $B \to \psi X$ was proposed by Fritzsch[1] as a favorable mode for reconstructing b-flavored mesons. Subsequently others[2–5] discussed inclusive ψ production in B decay as a test for color suppression. The spectator diagram for the inclusive decay $B \to \psi X$ is shown in Fig. 1. A ψ can be produced only if the color of the $\bar{c}$ from the virtual W^- matches the color of the c. Ignoring the effects of gluons, the requirement of color matching reduces the decay amplitude by a factor of 3. This color suppression may be defeated by gluon radiation. Short-range enhancements brought about by gluon exchange may also alter the suppression factor; most theoretical estimates suggest they increase it. Recent estimates[2,4] of the inclusive branching ratio range from 0.3% to 2.4%.

Statistically weak evidence for $B \to \psi X$, with an inclusive branching ratio of about 1%, was first presented in 1984 (Ref. 6). More compelling evidence has been reported recently by CLEO (Ref. 7) and by ARGUS Collaborations.[8] Here we present a more extensive, updated report on the CLEO work. The data sample used here includes that of Refs. 6 and 7; the numbers given here supplant the numbers given there. We present measurements of the inclusive branching ratio for $B \to \psi X$, and the exclusive branching ratios for $B^- \to \psi K^-$ and $\bar{B}^0 \to \psi \bar{K}^{*0}$. (In this article, wherever a decay mode is specified, its charge conjugate is also implied.) From the exclusive decays we obtain new measurements of the masses of the charged and neutral B mesons. The momentum distribution of ψ's from $B \to \psi X$ is given and interpreted to provide information on the mass distribution of the hadronic system X. As a byproduct of this work, we obtain upper limits on ψ production from the continuum and from the $\Upsilon(1S)$.

II. EXPERIMENTAL PROCEDURE

The B mesons used in this study were produced by the reaction $e^+e^- \to \Upsilon(4S) \to B\bar{B}$, using the Cornell Electron Storage Ring (CESR). The decay products of the B's were observed in the CLEO detector. As the CLEO detector has been described in detail elsewhere,[9] only a brief description is given here.

Initially, the central region of the detector contained a three-layer cylindrical proportional chamber and a seventeen-layer cylindrical drift chamber inside a superconducting solenoid magnet of 1-m radius operating at 1.0 T. Later, the proportional chamber was replaced with a ten-layer cylindrical precision drift chamber, and the seventeen-layer drift chamber was instrumented to allow measurement of the specific ionization (dE/dx) of charged particles. In addition, the aluminum beam pipe was replaced by a thinner, beryllium beam pipe. Data used in this study were taken both with the original upgraded configurations.

Unchanged in the upgrade were the eight identical sectors of particle-identification apparatus outside the coil. Each sector consists of a three-layer planar drift chamber (closest to the magnet coil), a pressurized proportional-wire-chamber system used to measure specific ionization (dE/dx), an array of twelve time-of-flight scintillation counters, and, farthest from the intersection point, a 44-layer lead and proportional-tube shower chamber. The eight sectors are followed by 0.5–0.9 m of iron and a two-dimensional array of planar drift chambers for muon identification. Additional drift chambers are interspersed within the iron to allow identification of lower-momentum muons.

The data samples used in this study were 41 pb^{-1} at the $\Upsilon(4S)$ and 17 pb^{-1} at energies just below the $\Upsilon(4S)$ with the original detector configuration, 78 pb^{-1} at the $\Upsilon(4S)$, 36 pb^{-1} just below the $\Upsilon(4S)$, and 15 pb^{-1} at the $\Upsilon(1S)$ with the upgraded detector. Events were classified as hadronic events if they had at least five charged tracks, at least 30% of the center-of-mass energy visible as charged tracks, a common track vertex lying within 8 cm of the nominal interaction point along the beam line and within 2 cm transverse to the beam line, and at least 250 MeV of electromagnetic energy observed in the shower detector. The data samples consisted of 435 000 hadronic events at the $\Upsilon(4S)$, of which 125 000 events were $B\bar{B}$, 137 000 events in the continuum below the $\Upsilon(4S)$, and 275 000 events at the $\Upsilon(1S)$.

The decay modes $\psi \to e^+e^-$ and $\psi \to \mu^+\mu^-$ were used to detect ψ's. Electrons were identified by specific ionization and electromagnetic shower measurements, with a minimum momentum requirement of 1 GeV/c. At least one electron candidate was required to pass stringent electron identification requirements using both dE/dx and shower-detector information. The other was accepted if dE/dx or shower properties indicated it was probably an electron. Muons were identified by their ability to penetrate the iron hadron absorber. One of the two muons was required to pass through the full absorber, with a thickness of 0.5–0.9 m, and be detected by both planes of the outer chambers. The minimum momentum for that muon was 1.2–2 GeV/c, depending on the thickness of the iron traversed. The other muon was accepted if it passed through at least 0.3 m of iron, triggering at least two inner muon planes, and had a momentum above 1 GeV/c. In searching for $B \to \psi X$, an upper limit of 3.0 GeV/c was imposed on the muon momentum.

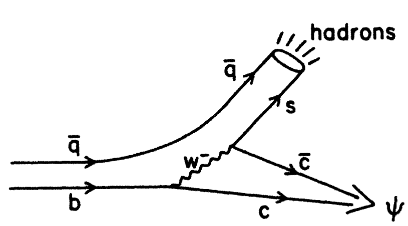

FIG. 1. The color-mixed spectator diagram for inclusive ψ production in B decay.

III. INCLUSIVE BRANCHING RATIOS

The dimuon-invariant-mass distribution from the $\Upsilon(4S)$ data sample is shown in Fig. 2. A strong ψ signal

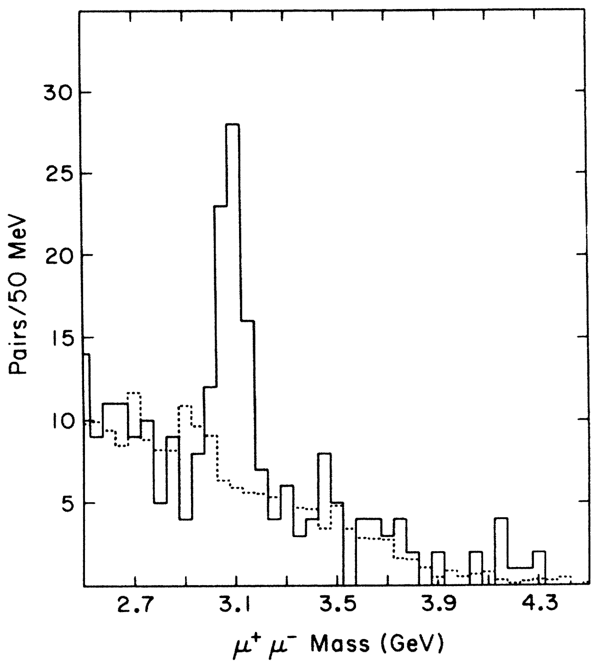

FIG. 2. $\mu^+\mu^-$ invariant-mass distribution in the neighborhood of the ψ mass (solid histogram). The dashed histogram shows the background calculated as described in the text.

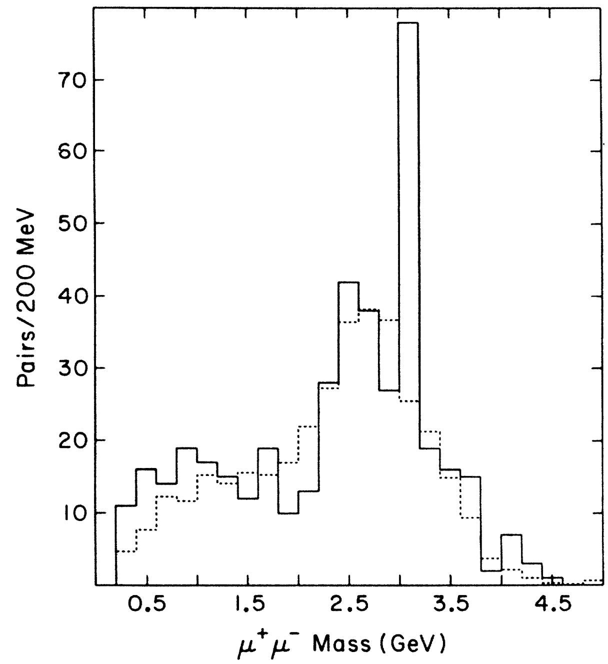

FIG. 3. $\mu^+\mu^-$ invariant-mass distribution from 0 to 5 GeV (solid histogram). The ψ signal should lie entirely in the 3.0—3.2-GeV bin. The dashed histogram shows the background calculated as described in the text.

is evident at 3.1 GeV. The shape of the background is modeled well by a Monte Carlo prediction (the dashed histogram), which is described below.

Apparent $\mu^+\mu^-$ pairs arise from several sources other than $\psi \to \mu^+\mu^-$: semileptonic decay of both B and $\bar{B}$ (44% of the background at the ψ mass); semileptonic decay of B to D, followed by semileptonic decay of D (20%); semileptonic decay of continuum D and $\bar{D}$ (7%); events with a muon from semileptonic decay of B or D and a hadron misidentified as a muon (25%); and events with two hadrons misidentified as muons (4%). These backgrounds were calculated, with no adjustable parameters, by Monte Carlo studies using known B and D semileptonic branching ratios[10] and misidentification probabilities measured with $\Upsilon(1S)$ data [1% (4.5%) per hadron, for penetration through full (partial) absorbers]. Because of uncertainties in the misidentification probabilities, the semileptonic branching ratios, and the D momentum spectra, the background calculations just described have an uncertainty estimated at $\pm 15\%$. We therefore choose to normalize the calculated background to the measured data in the intervals 2.4—3.0 and 3.2—3.8 GeV. The scaling factor so determined is 0.8 ± 0.1.

The sum of the background contributions, scaled by the factor 0.8, is compared with the measured dimuon mass distribution in Fig. 3. The nearness of the scaling factor to unity and the agreement of the shape of the calculated and measured distributions give us confidence that the background is adequately understood. The excess over background in the 3.0—3.2-GeV region is 52.5 ± 9.1 events, which we take as our ψ signal. The quoted error includes the statistical uncertainty in the scaling factor. An additional error has been included in the systematic error (see below) to allow for an uncertainty in the shape of the background.

To establish that the detected ψ's come from B decay, we examine the dimuon-invariant-mass distribution from the data sample at energies just below the $\Upsilon(4S)$ [shown in Fig. 4(a)]. There are two events in the 3.0—3.2-GeV region, with a background of 2.6 ± 0.7 events. Allowing for the difference in luminosity between the on-$\Upsilon(4S)$ and below-$\Upsilon(4S)$ data samples, these numbers imply that of the 52.5 ± 9.1 ψ events from the $\Upsilon(4S)$ data sample, at most 8 (90% C.L.) come from the continuum. Henceforth we will assume all 52.5 events are from $B\bar{B}$ decay.

The efficiency for detecting $\psi \to \mu^+\mu^-$ was determined by Monte Carlo simulation supplemented with measured efficiencies for the muon drift chambers. It was found to be nearly independent of ψ momentum, and to average 26% for ψ momenta below 2.0 GeV/c. Together with a $\psi \to \mu^+\mu^-$ branching ratio[11] of 0.074 ± 0.012 and our measured $\Upsilon(4S) \to B\bar{B}$ visible cross section of 1.06 nb, this leads to a branching ratio of

$$B(B \to \psi X) = (1.09 \pm 0.19 \pm 0.22)\% \ .$$

The 20% systematic error is composed of errors (summed in quadrature) in the $\psi \to \mu^+\mu^-$ branching ratio (16%), Monte Carlo efficiency (10%), muon-chamber efficiency (6%), and a 10% uncertainty in the background determination, which contributes a branching ratio error of 5%.

To place an upper limit on continuum ψ production at

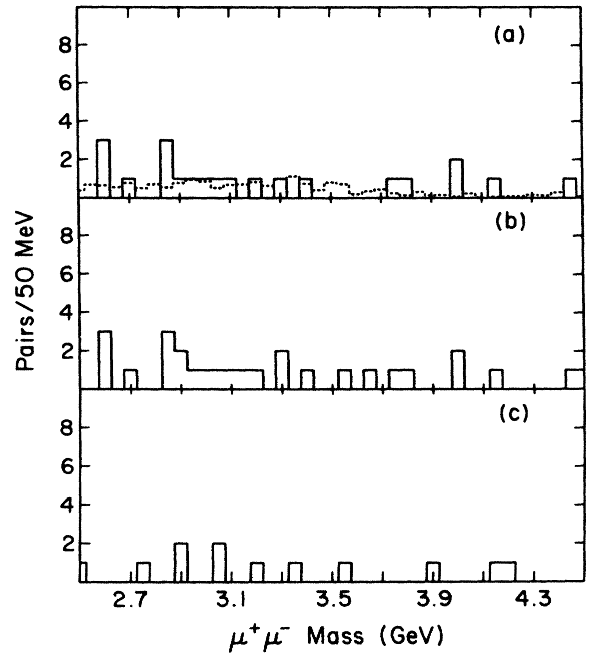

FIG. 4. $\mu^+\mu^-$ invariant-mass distributions in the neighborhood of the ψ mass. (a) Continuum data sample, at energies just below the $\Upsilon(4S)$. Cuts are as used on the $\Upsilon(4S)$ data sample. The dashed histogram shows the background calculated as described in the text. (b) Continuum data sample, with no upper limit cut on the momentum of the μ's. (c) $\Upsilon(1S)$ data sample, with no upper limit cut on the momentum of the μ's.

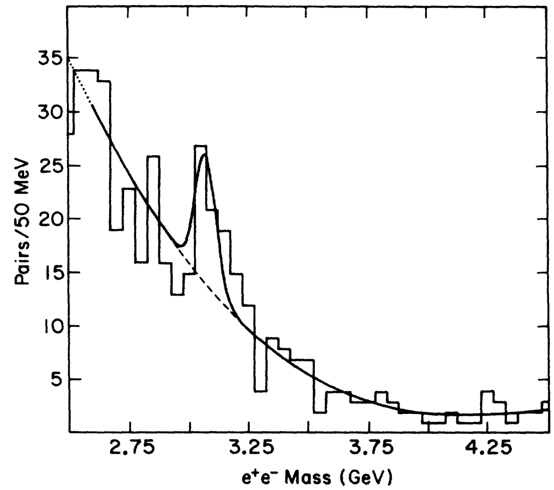

FIG. 5. e^+e^- invariant-mass distribution in the neighborhood of the ψ mass (histogram). The dashed curve represents the background as determined by a polynomial fit to the data, excluding the region of the ψ peak. The solid curve is a sum of the background and a Gaussian at the ψ mass, with the expected mass resolution.

all kinematically allowed momentum requires a modification of our cuts. The upper limit of 3.0 GeV/c on muon momentum imposed in the search for $B \to \psi X$ causes the ψ detection efficiency to fall at ψ momenta above 2 GeV. Dropping that cut, we obtain an efficiency that has no falloff at high ψ momentum. Again searching the continuum data sample, we find three events in the 3.0–3.2-GeV region, with a background of 3.2 ± 0.7 events [Fig. 4(b)]. This gives a 90%-confidence-level upper limit of 4 ψ's, leading to an upper limit on the yield of ψ per continuum event of 0.0011.

The $\Upsilon(1S)$ data sample has been searched for $\psi \to \mu^+\mu^-$ without the 3-GeV/c cut on muon momentum. The dimuon mass distribution is shown in Fig. 4(c). We have not modeled the background, but have taken it to be the average for dimuon masses in the intervals 2.4–3.0 and 3.2–3.8 GeV. There are three events in the signal region, with a background of 1. These numbers translate into a 90%-confidence-level upper limit on the branching ratio for $\Upsilon(1S) \to \psi X$ of 0.09%.

In searching for ψ by its e^+e^- decay mode, we have used only the data samples with the upgraded central detector configuration, because the dE/dx measurements in the 17-layer drift chamber provided significant improvement in electron identification. The dielectron-invariant-mass distribution from the $\Upsilon(4S)$ data sample is shown in Fig. 5. As in the dimuon case, a strong ψ signal is evident. We have not modeled the background, but have taken it to be a smooth curve through the bins near the ψ mass. The background curve is indicated in Fig. 5. There is an excess of 29.7 ± 8.4 events at the ψ mass. The data sample just below the $\Upsilon(4S)$ shows no sign of ψ. From this, and from the similar result with the dimuon decay mode, we conclude that all ψ's are from B decay.

The efficiency for detecting $\psi \to e^+e^-$ was determined by Monte Carlo simulation supplemented with separate investigations of electron identification efficiency. It was found to be 23%. Using this number along with the $\psi \to e^+e^-$ branching ratio and the $\Upsilon(4S)$ cross section leads to a branching ratio of

$$B(B \to \psi X) = (1.08 \pm 0.30 \pm 0.30)\% \ .$$

The 28% systematic error is composed of errors (summed in quadrature) in the $\psi \to e^+e^-$ branching ratio (16%), Monte Carlo efficiency (18%), electron identification efficiency (10%), and a contribution (10%) from uncertainty in the background subtraction.

The branching ratios obtained from dimuon and dielectron signals are combined to give

$$B(B \to \psi X) = (1.09 \pm 0.16 \pm 0.21)\% \ .$$

The 19% systematic error is dominated by the 16% error in the $\psi \to l^+l^-$ branching ratio.

IV. EXCLUSIVE DECAY MODES

The 78 dimuon events and 167 dielectron events in the ψ region were searched for two-body exclusive decays[12] of the B: $B^- \to \psi K^-$; $\bar{B}^0 \to \psi \bar{K}^0, \bar{K}^0 \to \pi^+\pi^-$; and $\bar{B}^0 \to \psi \bar{K}^{*0}$, $\bar{K}^{*0} \to K^-\pi^+$. No particle identification was required on the pion or kaon. B's produced in the reaction $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ have the same energy as the beams. The search procedure therefore constrained the candidate B-meson energy to the beam energy, and also constrained the dilepton mass to the ψ mass. In satisfying these constraints, the magnitudes, but not the directions, of particle momenta are readjusted, minimizing the χ^2 resulting from the shift from the measured values. The charged-particle momentum resolution, required for the χ^2 computation, was determined by studies with μ-pair data and with Monte Carlo simulation. A cut in χ^2 of 10 was found from Monte Carlo studies to have good efficiency and good background rejection. A dipion pair was classified as a K^0 if its mass was within 20 MeV of the K^0 mass; a K-π pair was classified as a K^{*0} if its mass was within 100 MeV of the K^* mass.

Four ψK^- events, no $\psi \bar{K}^0$ events, and 10 $\psi \bar{K}^{*0}$ events were found with masses above 5.2 GeV. The masses obtained are plotted in Fig. 6. A narrow peak at 5.280 GeV is evident.

The background to $B \to \psi K$ might arise from the following sources: (i) apparent dileptons with masses between 3.0 and 3.2 GeV which are in reality not ψ's (fake ψ's); (ii) real ψ's from the continuum; (iii) $B\bar{B}$ events, with a real ψ from one B, and the apparent K^- or $\bar{K}^{*0}$ from the other B; (iv) $B\bar{B}$ events, with a real ψ from one B, and the K^- or (at least part of the) $\bar{K}^*$ from the same B. The background from fake ψ's was studied using the sidebands to the ψ from data and using Monte Carlo simulation of non-ψ $B\bar{B}$ dileptons. The background from real ψ's from the continuum was studied using continuum data, with random high-momentum charged particles replaced with a ψ of the same momentum. The background from real

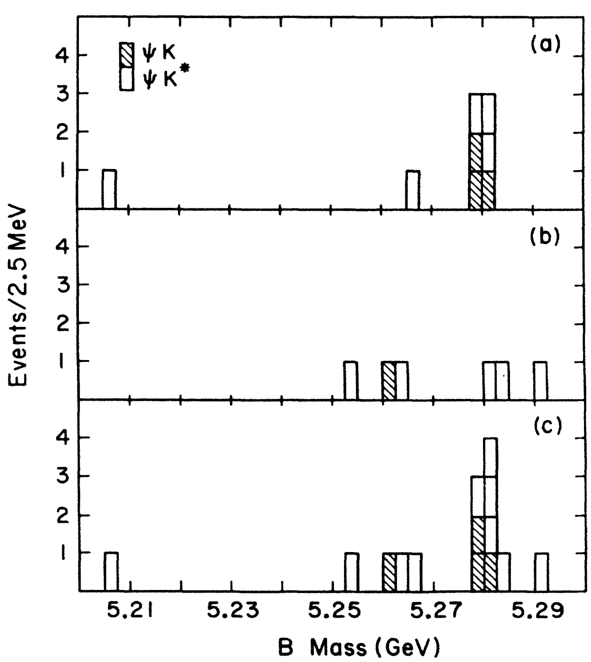

FIG. 6. B-meson mass distribution, for ψK^- and $\psi \bar{K}^{*0}$ decay modes. (a) ψ's detected by $\mu^+\mu^-$ decay mode, (b) ψ's detected by e^+e^- decay mode, (c) sum of (a) and (b).

ψ's from $B\bar{B}$ events was studied with Monte Carlo simulation. The only significant source was item (iv). The calculated background within ± 6 MeV of the B mass peak was 0.1 ψK^- events and 0.5 $\psi \bar{K}^{*0}$ event.

The efficiency for detecting ψK^-, given that the ψ has been detected, was determined by Monte Carlo simulation to be 73%. The efficiency for detecting $\psi \bar{K}^0$, including the $\bar{K}^0 \to \pi^+\pi^-$ branching ratio, was found to be 15%. The efficiency for detecting $\psi \bar{K}^{*0}$, including the $\bar{K}^{*0} \to K^-\pi^+$ branching ratio, was found to be 37%. The exclusive branching ratios resulting from these efficiencies (assuming production rates for charged and neutral B's are in the ratio 60:40) are

$$B(\bar{B}^0 \to \psi \bar{K}^0) < 0.5\% \text{ at } 90\% \text{ C.L.} ,$$

$$B(B^- \to \psi K^-) = (0.09 \pm 0.05)\% ,$$

$$B(\bar{B}^0 \to \bar{K}^{*0}) = (0.41 \pm 0.18)\% .$$

Because background is so small, these reconstructed B's are well suited for a mass determination. The mass resolution is ± 2.8 MeV, and is dominated by the spread in beam energy. The three ψK^- events lead to a mass

$$m_{B^-} = (5.2801 \pm 0.0016 \pm 0.003) \text{ GeV} ,$$

while the five $\psi \bar{K}^{*0}$ events lead to a mass

$$m_{\bar{B}^0} = (5.2812 \pm 0.0013 \pm 0.003) \text{ GeV} .$$

The error in these numbers due to background is small compared to the measurement errors quoted. The systematic error comes from the uncertainty in the beam energy scale, and cancels in the mass difference

$$m_{\bar{B}^0} - m_{B^-} = 1.1 \pm 2.1 \text{ MeV} .$$

The mass measurement technique, constraining the B energy to the beam energy, directly measures the difference between the beam energy and the B mass. Averaging charged and neutral B's, we obtain

$$M(\Upsilon(4S)) - 2M_B = 18.5 \pm 2.1 \pm 2.0 \text{ MeV} ,$$

where the last error accounts for the possibility that the center-of-mass energy was not centered perfectly on the $\Upsilon(4S)$ resonance during the on-$4S$ runs.

V. ψ MOMENTUM DISTRIBUTION

Figure 7 shows the efficiency-corrected, background-subtracted ψ momentum distribution, combining muon and dielectron data. The non-ψ background for electrons was determined from sidebands to the ψ peak; for muons it was determined by Monte Carlo simulation, although a sideband technique gave the same result within error.

The ψ momentum distribution following from the spectator diagram of Fig. 1 is readily calculated[13] if one ignores gluons and describes the initial $\bar{B}$ as a free $b\bar{q}$ system with the quarks in relative motion. We take for this Fermi motion a Gaussian with $\langle P_x^2 \rangle = \langle P_y^2 \rangle = \langle P_z^2 \rangle = (170 \text{ MeV}/c)^2$, as determined from the lepton spectrum in semileptonic B decay.[14] The $c\bar{c}$ mass is required to be near the ψ mass. Results depend only weakly

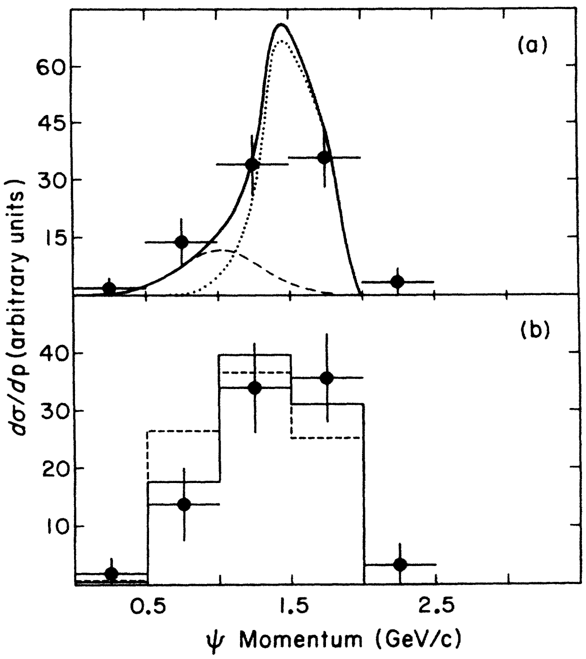

FIG. 7. ψ momentum distribution. In (a), the dotted curve is the spectator-model prediction for primary ψ's, the dashed curve is the spectator-model prediction for secondary ψ's (from ψ' and χ_1), and the solid curve is their sum. In (b) the dashed histogram is the calculated distribution assuming 40% of the decays are two body, 30% are $B \to \psi' X$ according to a spectator model, and 30% $B \to \psi X$, M_X uniformly distributed between 1.5 and 2.0 GeV. The solid histogram assumes 40% two body, 20% $B \to \psi' X$, 20% $B \to \psi X$, $1.0 < M_X < 1.5$ GeV, and 20% $B \to \psi X$, $1.5 < M_X < 2.0$ GeV.

on final-state quark masses, but are sensitive to the b-quark mass. We allow the b-quark mass to vary with Fermi momentum as

$$(m_b{}^2 + p^2)^{1/2} + (m_q{}^2 + p^2)^{1/2} = M_B \ .$$

The shape of the resulting ψ momentum spectrum is shown as the dotted curve in Fig. 7(a). This curves falls short of the data at low ψ momentum.

Not all ψ's detected from B decay need be primary decay products. Some might result from $B \to \psi' X$, $\psi' \to \psi \pi\pi$, or from $B \to \chi X$, $\chi \to \psi\gamma$. Kuhn, Nussinov, and Ruckl[2] calculate the ψ' and χ production, relative to primary ψ production, to be $\psi' : \chi_2 : \chi_1 : \chi_0 : \psi = 0.31 : 0.0 : 0.27 : 0.0 : 1.0$. Multiplying these production ratios by the branching ratios[11] of ψ' and χ to ψ, one obtains $0.16 : 0.0 : 0.08 : 0.0 : 1.0$ as the ratios for production of primary or secondary ψ. The ψ momentum distribution of these secondary ψ's is readily calculated in the framework of a spectator model for $B \to \psi' X$, or $B \to \chi X$. The resulting distribution, normalized relative to primary ψ production, is shown as the dashed curve in Fig. 7(a). This contribution accounts for a portion of the excess events at low ψ momentum. The solid curve in Fig. 7(a) is the sum of primary and secondary ψ curves. It represents the data adequately, suggesting that $B \to \psi' X$ is at least a partial explanation[15] for the low-momentum ψ's.

In the reaction chain $\Upsilon(4S) \to B\bar{B}$, $B \to \psi X$, the ψ laboratory momentum distribution is uniquely determined by the mass distribution of the hadronic system X. Determining the mass distribution from the momentum distribution cannot be uniquely done, due to the motion of the B mesons. Nonetheless, we examine the implications of the measured ψ momentum distribution for the X mass distribution. This analysis complements the spectator-model treatment given above, providing a different way of viewing the same information.

If one assumes that the branching ratios for $\bar{B}^0 \to \psi \bar{K}^0$ and $B^- \to \psi K^-$ are equal, and that those for $\bar{B}^0 \to \psi \bar{K}^{*0}$ and $B^0 \to \psi K^{*-}$ are also equal, then the measured exclusive branching ratios imply that $(46 \pm 17)\%$ of ψ production results from the two-body modes ψK and ψK^*. We take 40% as two-body decay, and try various possibilities for the remaining 60%: (1) $B \to \psi X$, with M_X distributed flat from 1.0 to 1.5 GeV; (2) $B \to \psi X$ with M_X distributed flat from 1.5 to 2.0 GeV; and (3) $B \to \psi' X$ according to a spectator quark model. Since possibility (1) does not contribute to the ψ momentum bin between 0.5 and 1.0 GeV, there must be some contribution to ψ production from (2) or (3). Possibilities (2) and (3) have similar ψ momentum distributions, and cannot be distinguished.[15] Figure 7(b) contains the same data as Fig. 7(a). The dashed curve is the calculation for 40% two-body decays, with the remaining 60% equal amounts of $\psi' X$ and ψX; M_X is between 1.5 and 2.0 GeV. This curve appears to overestimate the low-momentum contribution. The solid curve is the calculation for 40% two-body decays, 20% ψX with M_X between 1.0 and 1.5, and 40% a mix of ψX with M_X between 1.5 and 2.0, and $\psi' X$. It represents the momentum distribution well.

VI. DISCUSSION AND CONCLUSIONS

The measured inclusive branching ratio $B(B \to \psi X) = (1.09 \pm 0.16 \pm 0.21)\%$ agrees with previously reported CLEO (Refs. 6 and 7) measurements $(1.0^{+0.5}_{-0.4})\%$ and $(1.10 \pm 0.21 \pm 0.23)\%$, and supersedes them. It is also in good agreement with the ARGUS (Ref. 8) value: $(1.37^{+0.6}_{-0.5})\%$.

Theoretical predictions fall into three groups. Rough estimates[1,5] which ignore color matching or assume it will be accomplished by soft-gluon emission predict an inclusive branching ratio near 3%. Calculations which include a color suppression factor of $\frac{1}{9}$, allowing for color matching but ignoring hadronic enhancements,[2,3] predict 1.6–3.0%. Detailed QCD calculations[2,4] predict 0.3–0.5%. Our number lies between the second and third group, suggesting that color matching plays a significant role.

The measured exclusive branching ratios $B(B^- \to \psi K^-) = (0.09 \pm 0.05)\%$ and $B(\bar{B}^0 \to \psi \bar{K}^{*0}) = (0.41 \pm 0.18)\%$ show that roughly half of the inclusive $B \to \psi X$ decay is to the two-body modes ψK and ψK^*. This result is in agreement with the simple spectator-model calculation for $B \to \psi X$, which suggests that the hadronic object X will have a mass less than 1 GeV in 50%

of all cases. A more refined calculation of the two-body branching ratios is needed.

The measured B-meson masses are higher[16] than those previously measured by CLEO (Ref. 6). The available kinetic energy in $\Upsilon(4S) \to B\bar{B}$ is now measured as $M(\Upsilon(4S)) - 2M_B = 18.5 \pm 3.0$ MeV, as compared to 32 ± 5 MeV. The neutral-charged B mass difference is smaller, $M_{\bar{B}^0} - M_{B^-} = 1.1 \pm 2.1$ MeV, as compared to 4.0 ± 3.4 MeV (Ref. 6). Theoretical predictions[17] for the mass difference range from 2.3 to 5.8 MeV. The high end of these predictions now appears unlikely.

The measured ψ momentum distribution has a smaller low-momentum contribution that CLEO's previously published[7] distribution. The momentum distribution implies substantial two-body decay, $B \to \psi K/K^*$ (in agreement with direct measurements), but also substantial decay $B \to \psi' X$, or substantial decay $B \to \psi X$, $M_X > 1.5$ GeV (or some combination). A heavy hadronic system X suggests hard-gluon emission.

ACKNOWLEDGMENTS

We are grateful for the excellent efforts of the Cornell Electron Storage Ring staff which made this work possible. This work was supported by the National Science Foundation and the U.S. Department of Energy. Thanks are due from two of us (H.K. and R.K.) to the Department of Energy Outstanding Junior Investigating program and from one of us (K.K.) to the Mary Ingraham Bunting Institute for their support.

---

*Present address: Physics Department, Carnegie-Mellon University, Pittsburgh, PA 15213.

†Present address: Blackett Laboratory, Imperial College, London, United Kingdom SW7 2AZ.

‡Present address: Department of Physics, University of South Carolina, Columbia, SC 29208.

[1]H. Fritzsch, Phys. Lett. **86B**, 343 (1979).

[2]J. H. Kuhn, S. Nussinov, and R. Ruckl, Z. Phys. C 5, 117 (1980); J. H. Kuhn and R. Ruckl, Phys. Lett. **135B**, 477 (1984).

[3]T. DeGrand and T. Toussaint, Phys. Lett. **89B**, 256 (1980); M. B. Wise, *ibid.* **89B**, 229 (1980).

[4]P. H. Cox, S. Hovater, S. T. Jones, and L. Clavelli, Phys. Rev. D 32, 1157 (1985).

[5]I. Bigi and A. Sanda, Nucl. Phys. **B193**, 98 (1981).

[6]CLEO Collaboration, R. Giles *et al.*, Phys. Rev. D **30**, 2279 (1984).

[7]CLEO Collaboration, P. Haas *et al.*, Phys. Rev. Lett. 55, 1248 (1985).

[8]ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. **162B**, 395 (1985).

[9]CLEO Collaboration, D. Andrews *et al.*, Nucl. Instrum. Methods **211**, 47 (1983).

[10]CLEO Collaboration, A. Chen *et al.*, Phys. Rev. Lett. 52, 1084 (1984); Mark III Collaboration, R. M. Baltrusaitus *et al.*, *ibid.* **54**, 1976 (1985).

[11]Particle Data Group, M. Aguillar-Benitez *et al.*, Rev. Mod. Phys. **56**, S1 (1984).

[12]Our earlier publication (Ref. 7) noted two examples of the decay $B^- \to \psi K^{*-}, K^{*-} \to K_S^0 \pi^-$. Our present search finds no such events in the B mass peak. (Our procedures have changed slightly, and we no longer search for $\psi \to e^+e^-$ in the data sample with the original detector configuration.) Because of these inconclusive results, we prefer to quote neither a value nor an upper limit for the $B^- \to \psi K^{*-}$ branching ratio.

[13]V. Barger, W. Y. Keung, J. P. Leveille, and R. J. N. Phillips, Phys. Rev. D **24**, 2016 (1981).

[14]E. H. Thorndike, in *Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energies,* Kyoto, Japan, 1985, edited by M. Konuma and K. Takahashi (Research Institute for Fundamental Physics, Kyoto University, Kyoto, 1986), p. 406.

[15]We have searched for inclusive ψ' production in B decay in both the $\psi' \to l^+l^-$ and $\psi' \to \pi^+\pi^-\psi, \psi \to l^+l^-$ decay modes. We find no compelling evidence for ψ', but neither can we rule out that all of the low-momentum ψ's are of this origin.

[16]This higher mass value is also seen in other decay modes, $D^{*+}\pi^-$ and $D^0\pi^-$, for example (CLEO work in progress). Explanations will be discussed in a forthcoming publication.

[17]L.-H. Chan, Phys. Rev. Lett. 52, 253 (1983); E. Eichten, Phys. Rev. D 22, 1819 (1980); V. S. Mathur and M. T. Yamawaki, *ibid.* **29**, 2057 (1984).