PHYSICAL REVIEW D
PARTICLES AND FIELDS

THIRD SERIES, VOLUME 36, NUMBER 5 — 1 SEPTEMBER 1987

Exclusive decays and masses of the B mesons

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, S. Nandi, E. Nordberg, M. Ogg, D. Perticone, D. Peterson, M. Pisharody, K. Read, D. Riley, A. Silverman, and S. Stone
Cornell University, Ithaca, New York 14853

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

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

T. Bowcock, R. T. Giles, 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, E. H. Thorndike, and P. Tipton
University of Rochester, Rochester, New York 14627

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

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

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

A. Bean, G. J. Bobbink, I. C. Brock, A. Engler, T. Ferguson, R. W. Kraemer, C. Rippich, and H. Vogel
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213
(Received 25 February 1987; revised manuscript received 26 May 1987)

We report on the observation of exclusive decays of B mesons to modes containing a D or D^{*+} and one or two charged pions. From kinematic reconstruction we determine the masses of the neutral and charged B mesons to be $5280.6\pm0.8\pm2.0$ and $5278.6\pm0.8\pm2.0$ MeV, respectively. The mass difference is $2.0\pm1.1\pm0.3$ MeV. Branching ratios for these modes are given. From the charged-particle momentum spectrum in $\Upsilon(4S)$ decay, we find the average branching fraction for B-meson decay into a D or D^* plus a charged pion to be $(0.81\pm0.16)\%$. We find no signal for exclusive decays which would arise from the $b\to u$ transition and set upper limits for several such modes.

I. INTRODUCTION

Although many properties of B mesons can be inferred from inclusive measurements of $\Upsilon(4S)$ decay, some studies require the reconstruction of B decays. The masses of the neutral and charged B's are most accurately measured with reconstructed mesons. The mass difference between the neutral and charged B mesons, besides being interesting in the study of quark binding, is vital for estimating the relative amounts of $B^0\bar{B}^0$ and B^+B^- production in $\Upsilon(4S)$ decay and, hence, the total number of neutral and charged B mesons in the data sample. B-meson branching fractions represent a testing ground for theoretical models of B decay, and are especially interesting for separating spectator and nonspectator effects.[1] A sample of tagged B mesons of known charge allows one to use the other tracks in each event to measure B-decay multiplicities and branching ratios without systematic biases due to background rejection techniques. Exclusive final states without charmed particles can be used to measure the $b \rightarrow u$ transition.

The B mesons studied in this paper were produced in e^+e^- annihilations at the Cornell Electron Storage Ring (CESR) and the decay products were observed in the CLEO detector.[2] The results reported here include data from an extended run on the $\Upsilon(4S)$ resonance (run 2) and a reanalysis of data from a similar, earlier run (run 1). The current results supersede previously reported results based on the run 1 data sample alone.[3,4]

The CLEO detector has been described in detail elsewhere.[2] For run 1 the central detector consisted of a 3-layer proportional chamber surrounded by a 17-layer drift chamber. Both chambers operated in a 1.0-T magnetic field produced by a superconducting magnetic solenoid. Surrounding the magnet were eight identical octants used for particle identification. Each octant contained a 3-layer planar drift chamber, a set of pressurized proportional wire chambers capable of measuring the specific ionization (dE/dx) of charged tracks with an rms resolution of 6%, an array of time-of-flight counters (350-ps rms resolution), and a 12-radiation-length, lead and proportional-tube electromagnetic-shower counter. The octants were surrounded by 0.65–1.5 m of iron and a two-dimensional array of planar drift chambers for muon identification.

For run 2 there were two significant detector improvements.[5] First, a thin beryllium beam pipe (0.6% of a radiation length) and a precision vertex drift chamber replaced the original beam pipe and inner proportional chamber. This reduced multiple scattering and improved the momentum resolution for charged particles to a value of

$$(\delta p/p)^2=(0.007p)^2+(0.006)^2 ,$$

where p is in GeV/c. Second, the electronics of the 17-layer central drift chamber were upgraded to measure pulse height in addition to drift time, thus allowing identification of low-momentum charged particles by their specific ionization (dE/dx).

The run 2 data sample consists of an integrated luminosity of 78 pb^{-1} at the $\Upsilon(4S)$ resonance; the run 1 sample corresponds to 40 pb^{-1}. For background evaluations we also collected continuum data at energies just below $B\bar{B}$ threshold. The continuum data consist of an accumulation of 17 pb^{-1} in run 1 and 36 pb^{-1} in run 2. The total $\Upsilon(4S)$ sample includes 264 000 B mesons. Since the time of our previous publications, the run 1 data have been reprocessed using a significantly improved track-reconstruction program and a refined drift-time calibration of the central drift chamber.

Our most important hadronic selection requirements include the following.

(1) The total energy measured in the electromagnetic-shower counters must be greater than 0.25 GeV and less than 10.9 GeV.

(2) The total measured energy of charged and neutral particles must be between 30% and 170% of the center-of-mass energy.

(3) There must be at least three charged tracks.

(4) The reconstructed event vertex must be within 5 cm of the center of the interaction region in the direction parallel to the beams.

We have measured the masses of the charged and neutral B mesons (Sec. III), and the branching ratios for their decays into exclusive final states containing a D or D^{*+} meson and one or two charged pions (Sec. IV) by complete kinematic reconstruction of B-decay candidates. In Sec. V we use the charged-particle momentum spectrum from $\Upsilon(4S)$ decay to determine the $B\rightarrow D\pi^-$ branching ratio averaged over charge combinations. This measurement is independent of D-decay branching ratios.

The ratio of the amplitudes for the $b\rightarrow u$ and $b\rightarrow c$ quark transitions is determined by the corresponding ratio of the elements of the Kobayashi-Maskawa mixing matrix:[6] $|V_{ub}/V_{cb}|$. Studies of the lepton spectrum in semileptonic B decay[7,8] have led to an upper limit on this quantity of 0.16 at 90% confidence level. If the $b\rightarrow u$ transition rate is not much smaller than implied by this limit, one might expect to observe two-body decay modes such as $B\rightarrow\pi\pi$ and $B\rightarrow\rho\pi$ (which are analogous to $B\rightarrow D\pi$ and $B\rightarrow D^*\pi$ for the $b\rightarrow c$ transition) with branching fractions of the order of 0.02% (see Sec. VI). We determine upper limits for various two-body B-meson decays which would arise from the $b\rightarrow u$ transition both by studying the charged-particle momentum spectrum (Sec. V) and by attempting complete reconstruction (Sec. VI). Throughout this paper, unless otherwise stated, any decay mode discussed will also imply its charge-conjugate mode, which is assumed to be equal. For example, the measurement of the branching ratio for $B^-\rightarrow D^{*+}\pi^-\pi^-$ is the average for this mode and $B^+\rightarrow D^{*-}\pi^+\pi^+$.

II. B-MESON RECONSTRUCTION

All events considered for analysis passed our standard criteria for hadronic events.[9] We searched for events with charged tracks satisfying the kinematic constraints for the following low-multiplicity B-decay modes (including their charge conjugates):

$$B^-\rightarrow D^0\pi^- , \tag{1}$$

$$\bar{B}^0 \to D^0 \pi^+ \pi^- , \quad (2)$$

$$\bar{B}^0 \to D^+ \pi^- , \quad (3)$$

$$B^- \to D^+ \pi^- \pi^- , \quad (4)$$

$$\bar{B}^0 \to D^{*+} \pi^- , \quad (5)$$

$$B^- \to D^{*+} \pi^- \pi^- , \quad (6)$$

$$\bar{B}^0 \to D^{*+} \pi^+ \pi^- \pi^- . \quad (7)$$

In modes (5)–(7) the D^{*+} was required to decay to $D^0\pi^+$. The D mesons were detected using the decay modes $D^0 \to K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$.

The main difficulty in reconstructing exclusive B-meson decays is the very large number of random combinations which have an effective mass near the expected B mass. To reduce these we have developed stringent selection criteria. Particles assigned as kaons were required to have specific ionization in the inner drift chamber and outer dE/dx chambers and times of flight consistent with this identification (probability >0.20). Positive identification of kaon candidates from these devices (probability >0.75) was required for the decay $D^0 \to K^-\pi^+\pi^+\pi^-$ in mode (1), the decay $D^0 \to K^-\pi^+$ in mode (2), and the decay $D^+ \to K^-\pi^+\pi^+$ in mode (4). In order to improve the D-mass resolution, we corrected the measured momentum of tracks for energy loss by ionization in material upstream of the tracking system. We required the reconstructed D mass to be within two standard deviations of the known value.[10] The mass resolution for reconstructed D mesons has been determined by Monte Carlo simulation to be 10–24 MeV rms, depending on the decay mode. For modes (5)–(7) we required that the measured D^{*+}-D^0 mass difference be within three standard deviations of the known value; our expected resolution for this difference is 0.8–1.1 MeV rms, depending on the mode. In order to suppress false-hypothesis candidates for which we may have missed one or more particles, we cut on the difference ΔE between the measured energy of the B-decay products and the beam energy. The experimental resolution in ΔE is expected from Monte Carlo studies to be typically less than 40 MeV, depending on the mode. We required that $|\Delta E|$ be less than 90 MeV for all modes considered.

We performed a full kinematic reconstruction,[11] constraining the four-vectors of the charmed mesons (i.e., the D^0, D^+, or D^{*+}) to have the appropriate invariant mass, and the total energy of the B to be the beam energy. We required the χ^2 determined by kinematic fitting to be less than 3 per degree of freedom for all modes.[12]

In addition to the kinematic constraints, the angular distribution of the decay $D^0 \to K^-\pi^+$ can help to distinguish signal from background. The spin-zero D^0 decays isotropically in its rest frame. However, the decay angle θ^* of the K in the $K\pi$ rest frame with respect to the $K\pi$ direction in the laboratory tends to be strongly peaked near $\cos\theta^* = \pm 1$ for background processes. We therefore excluded candidate $D^0 \to K^-\pi^+$ decays with $|\cos\theta^*| > 0.9$. Also, the angular distribution of the B direction in the decay of the $\Upsilon(4S)$ is $\sin^2\theta$ with respect to the beam axis; to suppress continuum background we excluded candidates with $|\cos\theta| > 0.9$. A picture of a typical candidate event is shown in Fig. 1.

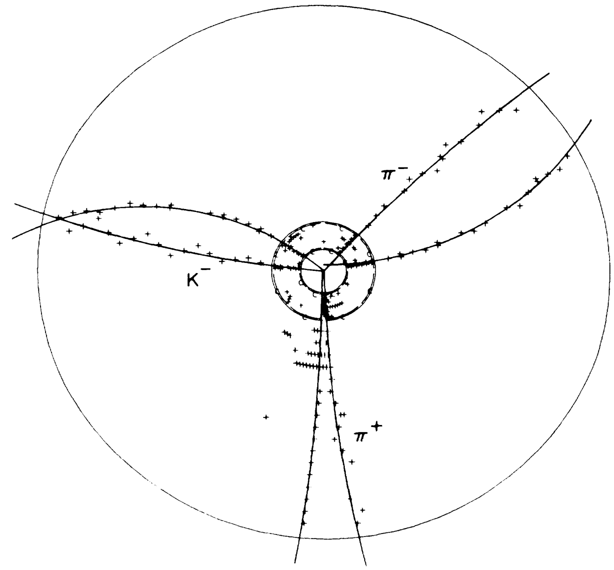

FIG. 1. Picture of a reconstructed $\Upsilon(4S) \to B^+B^-$, $B^- \to D^0\pi^-$ candidate event with the D^0 candidate decaying to $K^-\pi^+$. The B^+ decay is not reconstructed.

We compute the candidate B mass (M) from the relation

$$M^2 = (E_{\text{beam}})^2 - \left[\sum \mathbf{p}_i \right]^2 ,$$

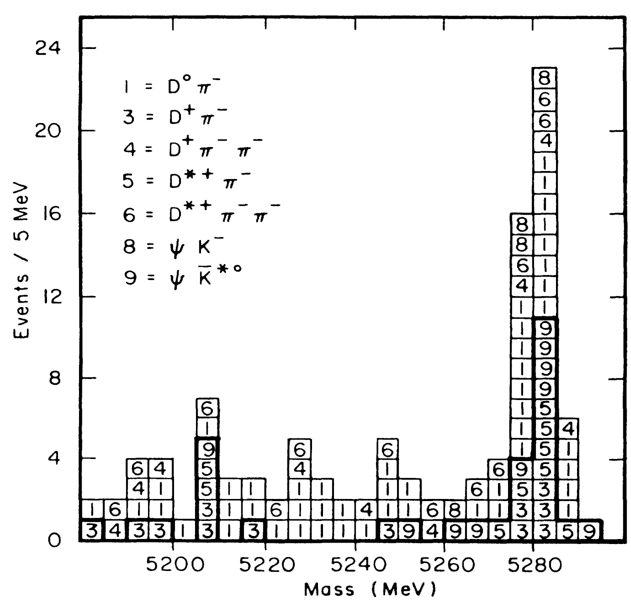

FIG. 2. Mass distribution of reconstructed B-decay candidates for modes (1) and (3)–(6), plus modes (8) and (9) reported in Ref. 14. Neutral modes lie below the heavy line. Modes (2) and (7) are treated separately (see text).

where $\mathbf{p}_i$ is the fitted three-vector momentum of the ith decay product and E_{beam} is the electron or positron beam energy. On the basis of Monte Carlo studies, this "beam-constraint" technique improves our mass resolution for B mesons by over an order of magnitude. The expected rms resolution in M, which is dominated by the spread of the beam energy in CESR, is 2.5–3.0 MeV, depending on the mode.

The beam-constraint technique causes the computed B mass to be sensitive to the effects of initial-state radiation since the beam energy used in the calculation is systematically higher than the true annihilation energy. We have simulated the effects of initial-state radiation[13] and estimate that the true masses of the neutral and charged B mesons are 0.7 ± 0.2 MeV below the values obtained using the beam-constraint technique.

Figure 2 shows the mass distribution of our candidates for the decay modes (1) and (3)–(6) from the combined runs 1 and 2 data samples. Mode (2) (see Fig. 3) and mode (7) (see Fig. 4) will be discussed separately. For completeness, Fig. 2 also includes 14 candidates for the decays $B^-\to\psi K^-$ and $\bar{B}^0\to\psi\bar{K}^{*0}$ [modes (8) and (9), respectively] which have been reported previously.[14] In Fig. 2 there is a clear peak near $M=5280$ MeV, but also a background extending to lower masses. In order to derive reliable masses and branching ratios for the B meson, we need to know how the background mass distribution behaves under the B peak.

We distinguish three classes of background: (i) spurious combinations of tracks in non-$B\bar{B}$ events from the continuum under the $\Upsilon(4S)$ peak, (ii) track combinations in $B\bar{B}$ events made with spurious D candidates, and (iii) spurious track combinations in $B\bar{B}$ events made with true D's. Backgrounds (i) and (ii) can be measured directly. The non-$B\bar{B}$ contribution (i) is determined by running at an e^+e^- center-of-mass energy just below $B\bar{B}$ threshold, and applying the same selection criteria [see Fig. 5(a) for modes (1) and (3)–(6)]. The event numbers in Fig. 5(a) are scaled to correspond to the same accumulated luminosity as in the $\Upsilon(4S)$ data and to correct for the $1/s$ dependence of the continuum cross section. The beam-constrained mass values are shifted up by the difference between the beam energy at the $\Upsilon(4S)$ and the actual continuum beam energy. The false D background (ii) is determined by repeating the $\Upsilon(4S)$ analysis with spurious D's taken from sideband mass combinations on each side of the true D-mass peak [Fig. 5(b)]. Since the two sidebands together cover twice the mass range ac-

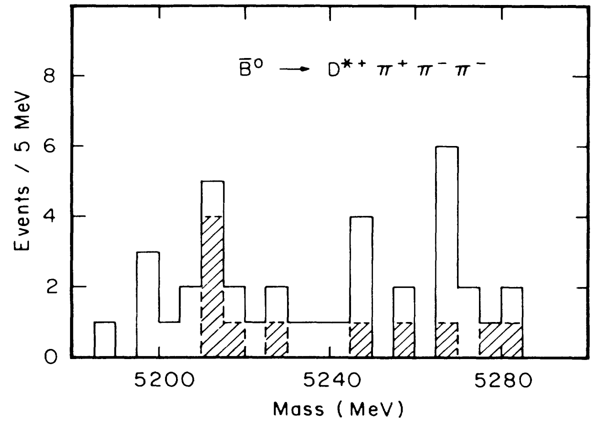

FIG. 4. Mass distribution of candidates for mode (7). The unshaded area corresponds to B decays in which the D^0 is observed to decay to $K^-\pi^+\pi^+\pi^-$; the shaded portion refers to $D^0\to K^-\pi^+$.

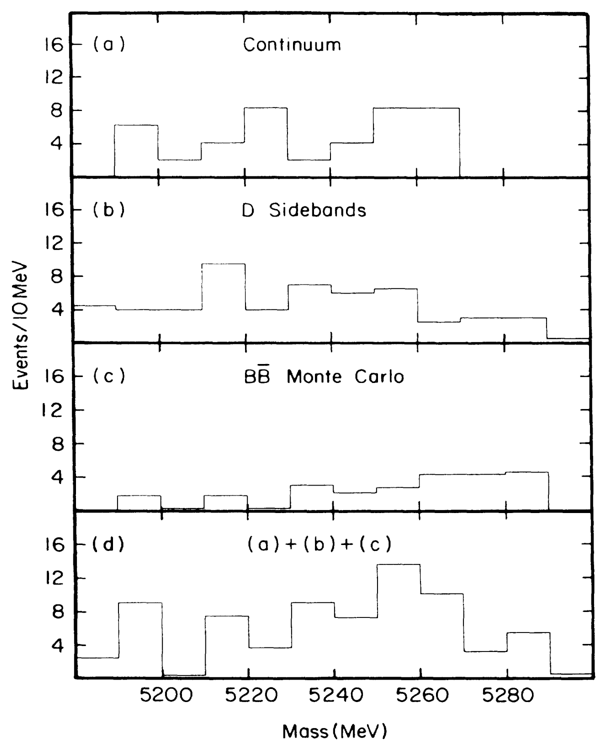

FIG. 5. Mass distributions of background contributions to modes (1) and (3)–(6): (a) the continuum contribution observed below $B\bar{B}$ threshold; (b) the spurious D contribution observed using D sidebands at the $\Upsilon(4S)$ resonance; (c) the contribution from $B\bar{B}$ with a correctly reconstructed D as simulated by the Monte Carlo method; (d) the sum of the contributions (a)–(c), with the D sidebands from below-threshold data subtracted. Note that the bin width is twice that for Fig. 2.

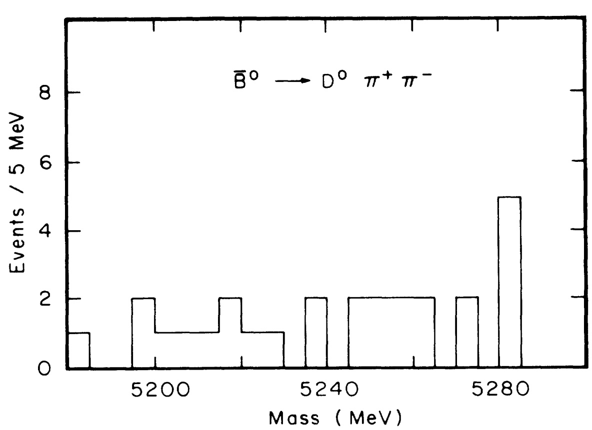

FIG. 3. Mass distribution of candidates for mode (2).

cepted in the signal analysis, the results in Fig. 5(b) have been scaled down by one-half.

We estimate the remaining background (iii) by Monte Carlo simulation. We generate $B\bar{B}$ events according to a model of spectator B decay plus fragmentation. The model assumes that the b quark always decays to a c quark and a W^- boson. The W^- is fragmented using a Feynman-Field model provided by the Lund Monte Carlo model.[15] The c quark and the spectator antiquark are paired to form a D or D^* which decays according to the measured branching ratios.[10] The decay products are propagated through the simulated detector and our normal analysis stream. We use the Monte Carlo track correlation list to check the identity of each track. Only those B candidates which contained a correctly reconstructed D decay but an incorrectly reconstructed B decay are used. The resulting mass distribution for the class (iii) background in modes (1) and (3)–(6) is shown in Fig. 5(c). Figure 5(d) shows the combined background prediction, obtained by summing the three contributions and subtracting the overlap between Figs. 5(a) and 5(b) using the D-sideband data from the continuum running.

A particularly insidious subset of the class (iii) background is the "feed-down" events in which we have observed all but one of the products in a true B decay. For example, we may have missed an additional pion, or in decays assigned to modes (1)–(4), the low-momentum π or γ from a $D^* \to D$ decay. If the missed particle has low momentum, the reconstructed beam-constrained B mass will be almost correct; the only chance of rejecting this solution will be if it fails the ΔE cut. An indication of the significance of this background is seen in Fig. 6, where we have plotted wrong-sign mass combinations, which cannot be correctly reconstructed B decays. Each of the candidates at the expected B mass is likely to be a case in which we have missed a charged pion from a true right-sign decay. Although Monte Carlo simulations indicate that our 90-MeV limit on acceptable $|\Delta E|$ values effectively suppresses the feed-down effect for modes (1) and (3)–(6), this cut is less effective for modes (2) and (7) (Figs. 3 and 4), because of the lower average momentum of the pions [especially in mode (7)], and because of the possibility of a missed π or γ from a $D^* \to D$ decay for mode (2) (Ref. 16). If feed down is important, the background distribution will peak close to the expected B mass. We therefore exclude modes (2) and (7) from the following analysis.[17]

The feed down may have been a significant contamination for modes (1), (2), and (6) in our previously published analysis[3,4] in which the ΔE resolution was about 90 MeV and the effective cut on $|\Delta E|$ (actually a χ^2 cut) was larger than the pion mass.

III. B-MESON MASSES

We determine the neutral and charged B-meson masses by fitting the beam-constrained mass distribution for the two-body decay modes [(1), (3), (5), (8), and (9)]. We use the two-body decays since they have very little background in the peak region. The studies discussed in the previous section indicate that the background in this subset of modes should also be flat near the region of the B mass. This is confirmed by the mass distributions shown in Figs. 7 and 8. The fits are performed using a Gaussian plus a flat background over the mass range from 5180 to 5291 MeV. (See Figs. 7 and 8.) The rms width of the Gaussian is set to 2.6 MeV based on Monte Carlo studies. After decreasing the means from the fits by 0.7 ± 0.2 MeV to correct for the effects of initial-state radiation, the resulting neutral- and charged-B masses are

$$M_{\bar{B}^0} = 5280.6\pm0.8\pm2.0 \text{ MeV}$$

and

$$M_{B^-} = 5278.6\pm0.8\pm2.0 \text{ MeV} ,$$

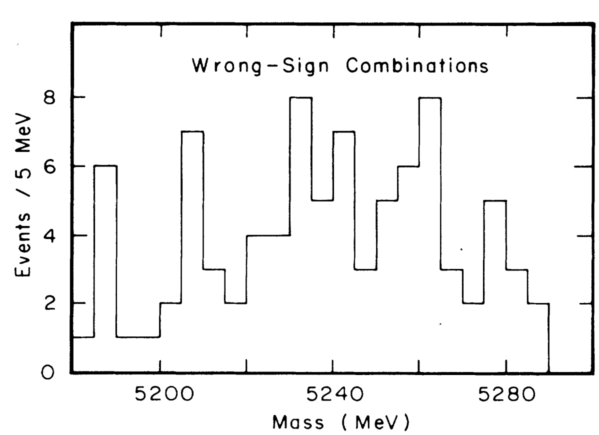

FIG. 6. Observed mass distribution of wrong-sign candidates for the combinations: $D^0\pi^+$, $D^+\pi^+$, $D^+\pi^+\pi^-$, $D^{*+}\pi^+$, $D^{*+}\pi^+\pi^-$, and charge conjugates.

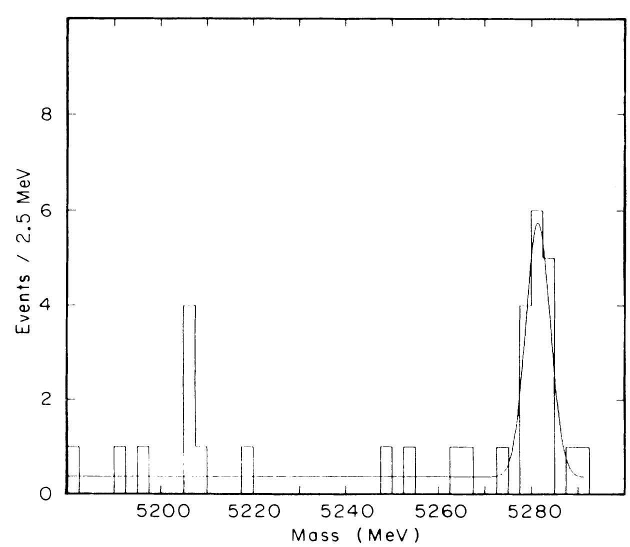

FIG. 7. Fit to the mass distribution of two-body neutral-B candidates using a Gaussian peak plus a flat background as described in the text.

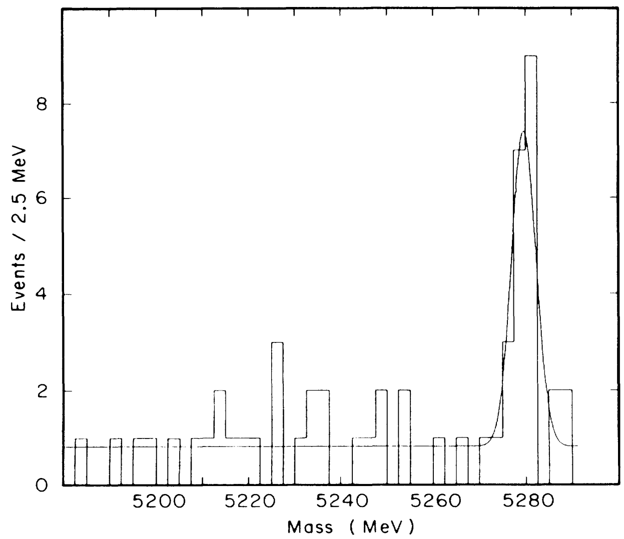

FIG. 8. Fit to the mass distribution of two-body charged-B candidates using a Gaussian peak plus a flat background as described in the text.

where the errors are statistical and systematic, respectively. The systematic errors arise from uncertainties in the CESR beam-energy calibration (1.8 MeV for the run 2 data, 2.3 MeV for the run 1 data), in the background shape (0.3 MeV), and in the fitting method (0.3 MeV). The measured mass difference has a smaller systematic error because it is independent of the absolute beam-energy calibration:

$$M_{\bar{B}^0}-M_{B^-}=2.0\pm1.1\pm0.3\text{ MeV} .$$

This result is consistent with several theoretical predictions.[18] Predictions of the mass difference have ranged from 1 to 6 MeV (Ref. 19). Since we use the beam-energy constraint in the calculation, the directly measured quantity is actually the difference between the mass of the $\Upsilon(4S)$ [10 580.0±3.5 MeV (Ref. 20)] and twice the B mass:

$$M(\Upsilon(4S))-2M_{\bar{B}^0}=18.8\pm1.7\pm2.0\text{ MeV}$$

and

$$M(\Upsilon(4S))-2M_{B^-}=22.8\pm1.7\pm2.0\text{ MeV} .$$

Although the difference between the $\bar{B}^0$ and B^- meson masses is in agreement with our published value,[4] the previous B-mass values are about 6 MeV lower than the present results. Besides the statistical uncertainty, there are two explanations: (1) the CESR single-beam energy calibration used in the run 1 analysis is now known to have been wrong by 2.3 MeV, and (2) the average masses may have been lowered if there was feed-down background included in the earlier analysis. To give credence to this hypothesis, we note that the higher-mass candidates from our previous publications are retained to a greater extent than the lower-mass candidates [especially in mode (6)] by our new analysis procedure, which includes the ΔE requirement and improved track reconstruction. The masses reported here are consistent with results of the ARGUS Collaboration.[21]

If we were to assume that the relative amounts of $B^0\bar{B}^0$ and B^+B^- production in decays of the $\Upsilon(4S)$ are determined by p-wave phase space, our measured mass difference would imply that the branching ratio for $\Upsilon(4S)\to B^0\bar{B}^0$ is 43% (Ref. 22). However, Ono[23] argues that p-wave phase space is inappropriate and suggests an alternative description. Using his model and the masses presented above, we would infer that the branching ratio is close to 50%.

IV. B BRANCHING RATIOS

The background calculation shown in Fig. 5(d) indicates that, averaged over modes (1) and (3)–(6), the number of background events in the signal region (5265–5290 MeV) is consistent with the number one would get by a flat extrapolation of the background at lower masses (5180–5265 MeV). Similar plots for each individual mode are consistent with this behavior within statistics. The average background level in Fig. 2 (3.0 events/5 MeV between 5180 and 5265 MeV) is consistent with that indicated by Fig. 5(d) (3.2 events/5 MeV). Therefore, to obtain the net signal for each mode, we fit the mass distributions for each mode using a Gaussian plus a flat background. The mean of the Gaussian is fixed at the measured $\bar{B}^0$ or B^- mass (not corrected for initial-state radiation) presented in the preceding section and the rms width is set to 2.6 MeV as determined by Monte Carlo simulation. The number of detected events for each mode is determined by the amplitude of the Gaussian from the fit and is given in Table I.

To obtain branching ratios for modes (1) and (3)–(6), we divide our fitted signal by the total number of neutral or charged B decays, by the detection efficiency for the particular mode, and by the appropriate branching ratios for the D^{*+} and D decay. The total number of neutral and charged B-meson pairs is the total number of hadronic events observed at the $\Upsilon(4S)$ resonance minus the number of events observed below threshold, scaled for the difference in integrated luminosity and for the $1/s$ dependence of the continuum cross section. We assume the proportion of $B^0\bar{B}^0$ to B^+B^- events in the decay of the $\Upsilon(4S)$ is 43:57 as discussed above. The detection efficiencies for the various modes are obtained by Monte Carlo simulation of the decay and the properties of the detector. The efficiencies for almost all modes are between 9% and 36%, before including the D^{*+} and D decay branching ratios and the particle-identification efficiency. The efficiency for kaon identification by ionization energy loss and time of flight is measured by analyzing kaons from kinematically identified ϕ decays.[24] The efficiency for positive identification is typically 35%, depending on momentum. For $D^{*+}\to D^0\pi^+$, we use a branching ratio of $(60^{+8}_{-15})\%$ (Ref. 25). For $D^0\to K^-\pi^+$, $D^0\to K^-\pi^+\pi^+\pi^-$, and $D^+\to K^-\pi^+\pi^+$, we use the recent measurements by the Mark III Collaboration:[26] (4.2±0.4±0.4)%, (9.1±0.8±0.8)%, and (9.1±1.3

TABLE I. Number of events observed (and the statistical error) or 90%-confidence-level upper limits for various B-decay reactions. B-meson branching fractions (with statistical and systematic errors, respectively) or 90%-confidence-level upper limits. Charge-conjugate modes are assumed to have the same branching fractions.

Reaction	Number of events	Branching fraction (%)
$B^- \to D^0\pi^-$	$14.0^{+4.6}_{-3.9}$	$0.47^{+0.16+0.11}_{-0.13-0.08}$
$\bar{B}^0 \to D^0\pi^+\pi^-$	<10	<3.9[a]
$\bar{B}^0 \to D^+\pi^-$	$4.3^{+2.4}_{-2.1}$	$0.59^{+0.33+0.15}_{-0.29-0.14}$
$B^- \to D^+\pi^-\pi^-$	$1.2^{+2.0}_{-1.1}$	$0.25^{+0.41+0.24}_{-0.23-0.08}$
$\bar{B}^0 \to D^{*+}\pi^-$	$5.3^{+2.8}_{-2.2}$	$0.31^{+0.17+0.11}_{-0.13-0.07}$
$B^- \to D^{*+}\pi^-\pi^-$	$2.7^{+1.9}_{-1.7}$	$0.20^{+0.14+0.08}_{-0.13-0.05}$
$\bar{B}^0 \to D^{*+}\pi^+\pi^-\pi^-$	<15	<4.6[a]
$B^- \to D^{*0}\pi^-$	See text	0.27 ± 0.44[b]
$B^- \to \psi K^-$	3.0 ± 1.7	$0.09 \pm 0.06 \pm 0.02$
$\bar{B}^0 \to \psi \bar{K}^{*0}$	5.0 ± 2.2	$0.41 \pm 0.19 \pm 0.03$
$B^- \to \pi^0\pi^-$	<188	<0.23[c]
$\bar{B}^0 \to \rho^\pm\pi^\mp$	<376	<0.61[c,d]
$\bar{B}^0 \to \pi^+\pi^-$	<8	<0.03
$B^- \to \rho^0\pi^-$	<2	<0.02
$\bar{B}^0 \to \rho^0\rho^0$	<9	<0.05
$\bar{B}^0 \to \pi^\pm a_1(1270)^\mp$	<7	<0.12[d]
$\bar{B}^0 \to \pi^\pm a_2(1320)^\mp$	<4	<0.16[d]
$B^- \to \rho^0 a_1(1270)^-$	<52	<0.32
$B^- \to \rho^0 a_2(1320)^-$	<21	<0.23
$\bar{B}^0 \to p\bar{p}$	<6	<0.02

[a]The 90%-confidence-level upper limits on the number of events and branching ratio for this mode are calculated (conservatively) without subtracting any background.
[b]This branching ratio is inferred in Sec. V.
[c]The upper limit for this decay mode is obtained from analysis of the charged-particle momentum spectrum (Sec. V).
[d]The notation $\bar{B}^0 \to x^\pm y^\mp$ means that the limit quoted is for the sum of the branching ratios for $\bar{B}^0 \to x^+y^-$ and $\bar{B}^0 \to x^-y^+$.

± 0.4)%, respectively. Note that these D branching ratios are higher than those[27] used in our previous publications.[3,4]

We combine the results from the two D^0-decay modes with weights appropriate to their branching ratios times acceptance. The resulting B branching ratios are shown in Table I. For reasons mentioned above only 90%-confidence-level upper limits are given for modes (2) and (7) (Ref. 28). The previously reported[14] branching ratios for modes (8) and (9) are included for completeness. The systematic errors include uncertainties in the background subtraction [20% for most modes, 90% for mode (4)], in the efficiency calculation (5–25 %, depending on the mode), in the D and D^{*+} branching ratios (13–25 %), and in the proportion of neutral and charged B mesons in $\Upsilon(4S)$ decay (12%). The branching ratios we obtained previously from the run 1 data alone[4] were considerably higher than the present values, because of the smaller D branching ratios used, and perhaps because of the possible feed-down background and statistical fluctuations. Our measured B branching ratios are consistent with results of the ARGUS Collaboration.[21]

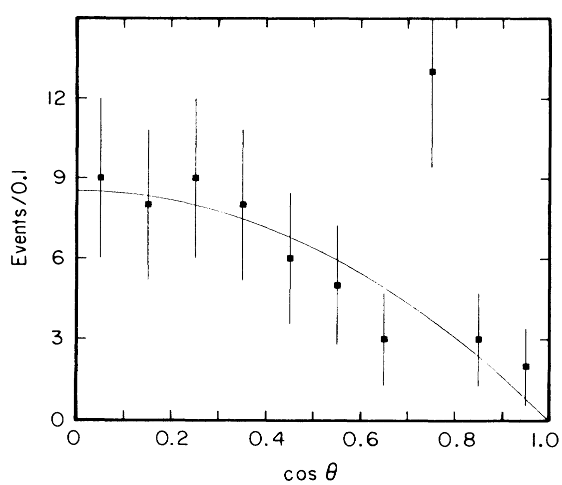

FIG. 9. Distribution in the cosine of the angle between the B candidate and the beam axis for modes (1)–(6), (8), and (9). A $\sin^2\theta$ curve is shown normalized to the same area as the data.

Figure 9 shows the angular distribution of the B-candidate direction with respect to the beam axis when the cut on this angle is removed from the event selection procedure. A χ^2 of 9 for 8 degrees of freedom is obtained when the distribution is fitted to the $\sin^2\theta$ distribution expected for the decay of a 1^- particle into two spinless particles.

V. $B \to D\pi^-$ BRANCHING RATIO

We now describe a simple measurement using the charged-particle momentum spectrum from $\Upsilon(4S)$ decay

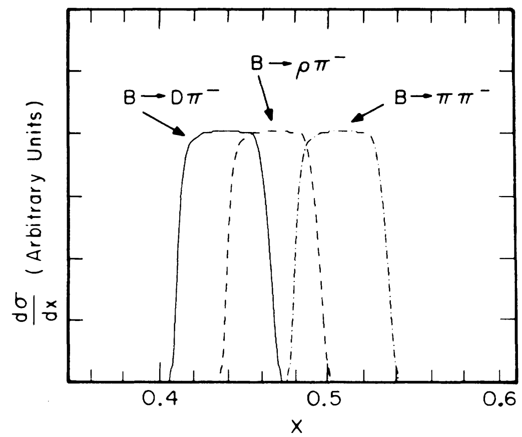

FIG. 10. Expected x distribution of the π^- for the three decays $B\to\pi\pi^-$, $\rho\pi^-$, and $D\pi^-$.

which gives the average of the $B\to D\pi^-$ branching fractions, where D here means D^0, D^+, D^{*0}, or D^{*+} and B means $\bar{B}^0$ or B^-. For this measurement we use the run 2 data sample only, which includes approximately 177 000 B mesons. This new measurement is significantly more precise than our previously reported results[4] which used the run 1 data sample. The results rely only on charged-particle momentum measurements in the central tracking chambers.

Consider the π^- momentum spectrum from two-body decays of B mesons, $B\to X\pi^-$, where the B mesons come from $\Upsilon(4S)$ decay. Since the B mesons are almost at rest[29] ($\beta_B=0.06$), the pions have a mean momentum determined by the mass of X, and a range of momenta determined by β_B. The π^- momentum distributions expected for the reactions $B\to\pi\pi^-$, $B\to\rho\pi^-$, and $B\to D\pi^-$ are shown in Fig. 10, plotted in terms of the variable x, defined as the π^- momentum divided by the beam energy. The $B\to D\pi^-$ contribution can come from any of four reactions: $B^-\to D^0\pi^-$, $B^-\to D^{*0}\pi^-$, $\bar{B}^0\to D^+\pi^-$, and $\bar{B}^0\to D^{*+}\pi^-$, all of which give essentially the same pion momentum spectrum. By comparing our data from B-meson decay to the distributions shown in Fig. 10, we first show that there is no visible signal in the x distribution for the charmless two-body decays $\pi\pi^-$ and $\rho\pi^-$; then we calculate the branching ratio for the $D\pi^-$ final state.

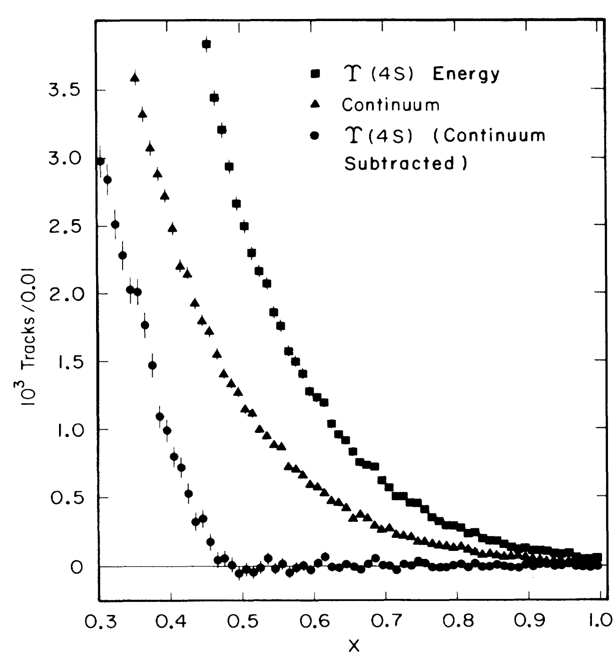

FIG. 11. The x distributions for the run 2 data sample from the $\Upsilon(4S)$, the nearby continuum below the $\Upsilon(4S)$, and the subtracted distribution with the continuum scaled.

In Fig. 11 we show the observed x distribution of charged tracks from data collected at the $\Upsilon(4S)$ resonance, the nearby continuum below the resonance, and the $B\bar{B}$ distribution obtained by subtracting the two, after scaling the continuum. To reduce bin-to-bin fluctuations in the continuum distribution, where no narrow structures are expected or observed, we fit the continuum data to an exponential of a third-order polynomial before subtracting it. We required the production angle of the charged tracks with respect to the direction of the colliding beams to be greater than 32° in order to ensure that we are dealing with well-measured tracks. This leaves an effective solid angle of 85% of 4π sr. We determine our track-finding efficiency to be 95% using a Monte Carlo simulation of the detector.

There are charged particles populating the x region between 0.40 and 0.47 in the subtracted distribution (Fig. 11), where the π^- from the $D\pi^-$ final state is expected. However, there is no net yield of particles beyond $x=0.47$ in the subtracted distribution. Using the momentum intervals corresponding to $x=0.49-0.53$ and $x=0.47-0.50$ for the $\pi\pi^-$ and $\rho\pi^-$ modes, respectively, and correcting for the acceptance and efficiencies discussed above, we find -233 ± 202 and 43 ± 258 charged particles consistent with having been produced in $B\to\pi\pi^-$ and $B\to\rho\pi^-$ decays, respectively. These measurements correspond to upper limits on the branching fractions for these decay modes of 0.13% and 0.26%, respectively, at 90% confidence level. These upper limits are about one order of magnitude larger than those found for the explicit channels $\bar{B}^0\to\pi^+\pi^-$ and $B^-\to\rho^0\pi^-$ discussed in Sec. VI. Assuming that the fractions of $\Upsilon(4S)$ decay at the resonance peak to $B^0\bar{B}^0$ and to B^+B^- are 0.43 and 0.57, respectively, we assign upper limits of 0.23% and 0.61% to the heretofore unlimited channels $B^-\to\pi^0\pi^-$ and $\bar{B}^0\to\rho^\pm\pi^\mp$ (Ref. 30). Since we expect the branching fractions to charmed mesons to be substantially larger than these limits, we ignore charmless B decays in the following analysis.

The charged-particle momentum spectrum from B decay for x greater than 0.35 includes contributions from several final states beside the $D\pi^-$ final state we want to measure. These include $D\pi\pi^-$, $D\pi\pi\pi^-$, $Xl^-\nu$, and DX where the D decays to a high-momentum charged pion. It is straightforward to subtract the last two spectra from the measured x distribution shown in Fig. 11. The muon and electron spectra from $B\to Xl\nu$ have been independently measured.[8] Their sum is shown in Fig. 12(a). We estimate the spectrum of particles from D decay from our measured D momentum spectrum[31] by assuming that B mesons decay to D mesons 100% of the time, and by using the published D branching ratios of the Mark III group.[32] This estimated spectrum is shown in Fig. 12(b). Note that the magnitude of the latter subtraction is small relative to the $D\pi^-$ signal in the high-x region. The resulting subtracted x distribution is shown in Fig. 12(c). We extract the amount of $D\pi^-$ by fitting this spectrum with a combination of $D\pi^-$, $D\pi\pi^-$, and $D\pi\pi\pi^-$ shapes. For the $D\pi\pi\pi^-$ component we use a phase-space distribution. For the $D\pi\pi^-$ we use three different shapes: (1) phase space, (2) $D\rho^-$, and (3) DW^- via $V-A$ decay with the W^- subsequently materializing into $\pi^0\pi^-$. The x distributions for these three models are shown in Fig. 12(c). In Fig. 13 we show the fit to the data using the phase-space $D\pi\pi^-$ and $D\pi\pi\pi^-$ distributions plus the $D\pi^-$ component. We also show the fit with the $D\pi^-$ component removed. Clearly, the $D\pi^-$ mode is necessary to fit the spectrum well. The branching fractions found for $D\pi^-$ are $(0.83\pm0.20)\%$, $(0.71\pm0.17)\%$, and $(0.76\pm0.18)\%$ for models (1), (2), and (3), respectively.

While the results using the three models are consistent, we can also extract a branching fraction without using the fitting procedure. Inspection of Fig. 12(c) shows that none of the models of $D\pi\pi^-$ decay produce pions above an x of 0.44. [Note that even the reaction $B\to D^{**}(2420)\pi^-$ produces no π^- above an x of 0.43.] The x distribution from the $D\pi^-$ decay, however, extends to x of 0.47. We can extract a model-independent branching ratio by simply measuring the number of events with x between 0.44 and 0.47 (659 ± 133 events) and then correcting for the fact that only 45% of $D\pi^-$ events lie within this interval. This technique gives an average $B\to D\pi^-$ branching fraction of $(0.81\pm0.16)\%$. We investigated several sources of systematic error in this method and found their contributions are all small in comparison with the statistical error. They include uncertainties in the B-meson mass (which produce a 1% error in the branching fraction), the continuum subtraction (4%), the relative amounts of D^0(or D^+)π^- and D^{*0}(or D^{*+})π^- (2%), and in the track-finding efficiency (3%).

We can write this branching ratio explicitly as a constraint equation relating the branching ratios for four independent reactions using the parameter f_0, which is the fraction of neutral $B\bar{B}$ production in $\Upsilon(4S)$ decay:

$$f_0[B(\bar{B}^0\to D^+\pi^-)+B(\bar{B}^0\to D^{*+}\pi^-)]+(1-f_0)[B(B^-\to D^0\pi^-)+B(B^-\to D^{*0}\pi^-)]=(0.81\pm0.16)\% .$$

This result is independent of the D^0, D^+, and D^{*+} branching ratios, and is the most precise determination of the weighted sum of these two-body B-decay branching fractions. It is consistent with our previous result:[4] $(1.0\pm0.30\pm0.25)\%$.

Using the value $f_0=0.43$, based on p-wave phase space as discussed above, and our measured branching ratios for modes (1), (3), and (5) presented in the preceding section, one can use the equation above to obtain a value of $(0.27\pm0.44)\%$ (Ref. 33) for the unmeasured $B^-\to D^{*0}\pi^-$ branching ratio which is consistent with recent theoretical predictions[34] and comparable to our measurement for $\bar{B}^0\to D^{*+}\pi^-$ [mode (5)].

There have been several theoretical predictions for the two-body B branching fractions. Early work[4,35] predicted a 1% branching ratio for each of the four $D\pi^-$ modes on average. Recently, a model[36] has been successfully applied to two-body charm decays which also could be used for two-body B decays. However, the predictions depend on a scale factor a_1^2, which is difficult to calculate. Estimates[37] based on charm decay give $a_1\approx1.1$. With this value of a_1, the branching fractions are predicted[37] to be 0.5% for $\bar{B}^0\to D^{*+}\pi^-$ and 0.6% for $\bar{B}^0\to D^+\pi^-$, which are consistent with our results. Other recent theoretical predictions[34] of the branching ratios for modes (1), (3), (5), and $B^-\to D^{*0}\pi^-$ are consistent with our measurement of $(0.81\pm0.16)\%$ for the weighted sum of these modes. Also, the individual values predicted[34] for modes (1), (3), and (5) are consistent with our measurements presented in the

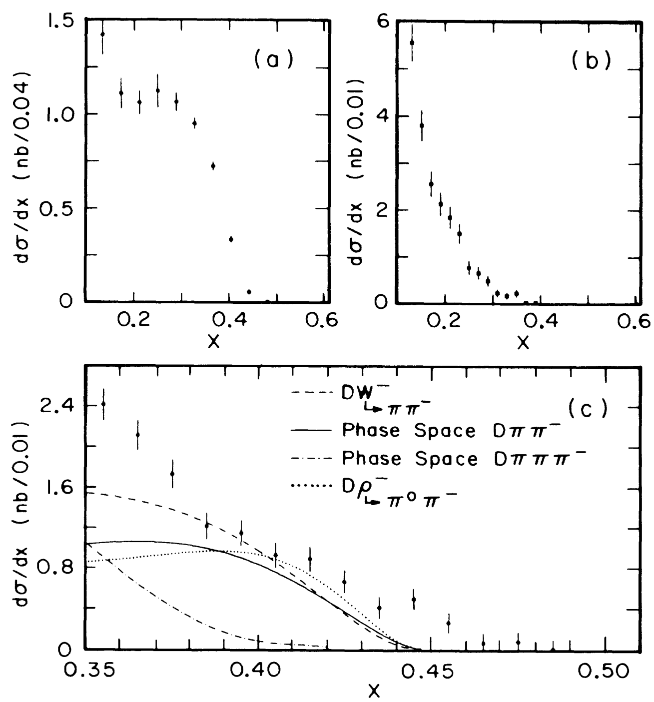

FIG. 12. (a) Measured lepton x spectrum from B decay (from Ref. 8); (b) the x distribution for the decay products of D's which arise from B decay; (c) the x distribution from the $\Upsilon(4S)$ with (a) and (b) subtracted (points) and for $D\pi\pi^-$ and $D\pi\pi\pi^-$ (curves).

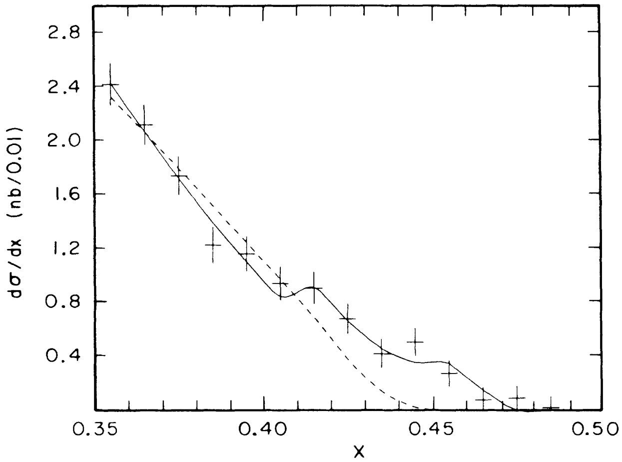

FIG. 13. Fit to data with phase-space models for $D\pi\pi^-$ and $D\pi\pi\pi^-$ with $D\pi^-$ included (solid line) and excluded (dashed line).

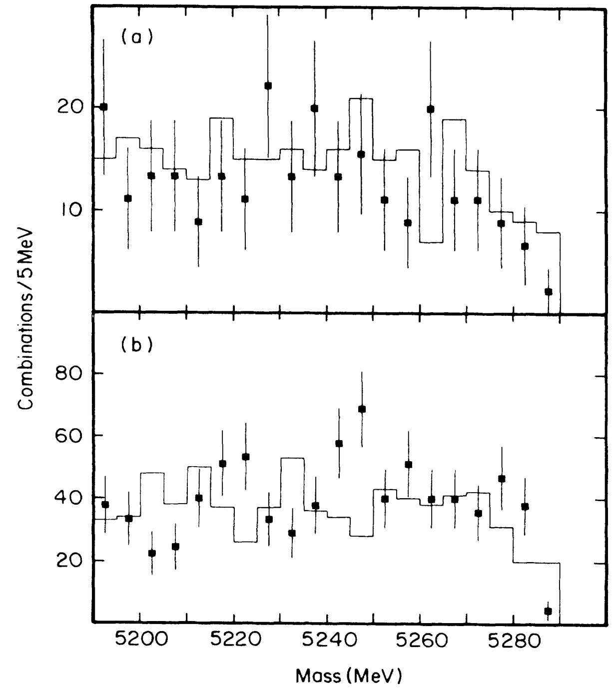

FIG. 14. Mass distributions of candidates for (a) $\bar{B}^0 \to \pi^+\pi^-$ and (b) $B^- \to \rho^0\pi^-$. The histograms represent candidates from the data taken on the $\Upsilon(4S)$ resonance and solid squares with error bars represent candidates from the scaled continuum data. The error bars reflect how much the scaling increases the statistical error associated with the continuum data.

preceding section.

Motivated by suggestions[38] that the branching ratio for $\psi(3770) \to D\bar{D}$ may be substantially less than 100%, we searched[39] for evidence of non-$B\bar{B}$ final states in $\Upsilon(4S)$ decay. One possible indication of such states is charged particles with $x > 0.5$. We see no evidence for charged particles above $x = 0.5$ in the $B\bar{B}$ distribution (21 ± 185 tracks) shown in Fig. 11. We can set an upper limit on $\zeta = [\Upsilon(4S) \to \text{non-}B\bar{B}]/[\Upsilon(4S) \to B\bar{B}]$ if we estimate how often non-$B\bar{B}$ decays make energetic decay products. Two such estimates were obtained by measuring the fraction of tracks with $x > 0.5$ both in the continuum data and in a sample of data from running at the $\Upsilon(1S)$ resonance. If the non-$B\bar{B}$ decays are like continuum events below $B\bar{B}$ threshold, the upper limit on ζ is 3.8% at 90% confidence level. If the non-$B\bar{B}$ decays are like the three-gluon decays of the $\Upsilon(1S)$, the upper limit on ζ is 13% at 90% confidence level.

VI. $b \to u$ TRANSITIONS IN TWO-BODY DECAY

In the spectator model of B-meson decay, the two-body decay $B \to X\pi^-$ occurs when the c or u quark and spectator quark form a meson X and the virtual W^- materializes as a π^-. In a $b \to u$ transition, one would expect X to be a π, ρ, $a_1(1270)$, or some more massive light-quark state. The branching ratio for $\bar{B}^0 \to \pi^+ a_1(1270)^-$ could be relatively large, since the W^- can turn into an $a_1(1270)$, as in τ-lepton decay.[40] Since the branching ratios for the individual two-body modes presented above (Secs. IV and V) are roughly 0.4% on average, one might naively expect that a similar fraction of $b \to u$ transitions would result in each of the two-body decays mentioned above. If so, the branching ratios for these decays could be as high as 0.02% (Ref. 8). Previously, we reported 90%-confidence-level upper limits of 0.05% and 0.06% on the branching ratios for the decays $\bar{B}^0 \to \pi^+\pi^-$ and $B^- \to \rho^0\pi^-$, respectively.[4] With additional data, we now widen our search to include the decays $\bar{B}^0 \to \rho^0\rho^0$, $\bar{B}^0 \to p\bar{p}$, $\bar{B}^0 \to \pi^\pm a_1(1270)^\mp$, $\pi^\pm a_2(1320)^\mp$, and $B^- \to \rho^0 a_1(1270)^-$, $\rho^0 a_2(1320)^-$. We include decay modes with an $a_2(1320)$ because it can decay into $\rho^0\pi^-$ like the $a_1(1270)$.

The data samples of runs 1 and 2 are used for this analysis. We define a ρ^0 as any $\pi^+\pi^-$ pair with invariant mass between 600 and 900 MeV. We reconstruct $a_1(1270)^-$ and $a_2(1320)^-$ mesons through their decay into $\rho^0\pi^-$. We call $\rho\pi$ candidates $a_1(1270)$ mesons if their invariant mass is between 1115 and 1435 MeV (Ref. 41), and $a_2(1320)$ mesons if it is between 1265 and 1375 MeV. After reconstructing candidate decays of these particles, we require the observed energy of the two-body system to be within 100 MeV of the beam energy. The limit on the energy difference was determined by a Monte Carlo simulation of the tracking chambers.

Since the ρ in $B^- \to \rho^0\pi^-$ is polarized in the helicity-zero state, we can further reduce the background for this decay mode. We define an angle θ_π in the following way: first, find the direction of the ρ in the B rest frame; then, find the direction of the π^+ in the ρ rest frame. The angle between these two directions is θ_π. The angular distribution is proportional to $\cos^2\theta_\pi$ for real B decay, while it is expected to be flat for the background. Therefore, we reject combinations with $|\cos\theta_\pi|$ less than 0.5, reducing the background by 50% and lowering the efficiency by only 12.5%.

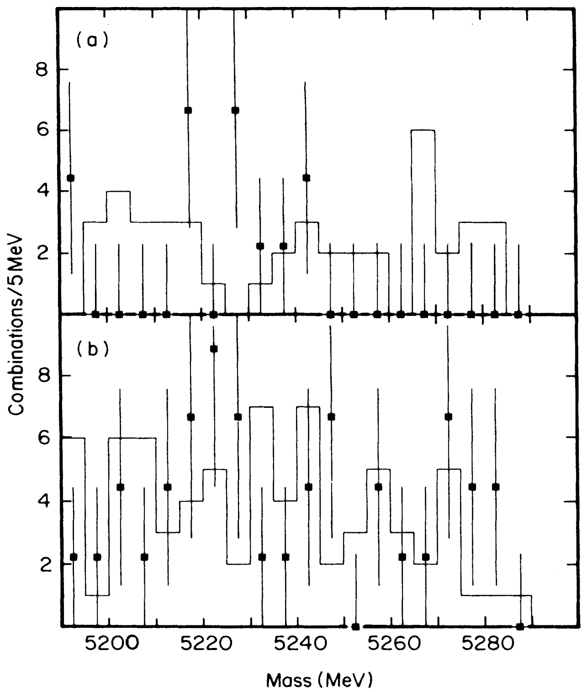

FIG. 15. Mass distributions of candidates after the $|\cos\theta|$ cut for (a) $\bar{B}^0 \to \pi^+\pi^-$ and (b) $B^- \to \rho^0\pi^-$. The histograms represent candidates from the data taken on the $\Upsilon(4S)$ resonance and solid squares with error bars represent candidates from the scaled continuum data.

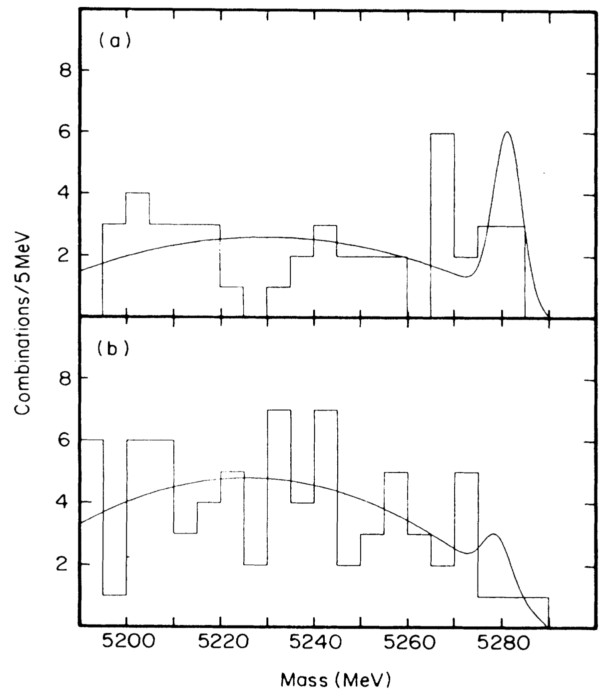

FIG. 16. Mass distributions of candidates from the $\Upsilon(4S)$ data for (a) $\bar{B}^0 \to \pi^+\pi^-$ and (b) $B^- \to \rho^0\pi^-$. The curves represent 90%-confidence-level upper limits.

For combinations which satisfy the above criteria we calculate the beam-constrained invariant mass (M) using the relation $M^2 = (E_{\rm beam})^2 - (\sum \mathbf{p}_i)^2$, where $\mathbf{p}_i$ is the measured three-vector momentum of the ith decay product. The mass distributions for two of the decay modes are shown in Fig. 14. For real B decay the distribution should peak at the measured mass of the appropriately charged B with an rms width of 3.0 MeV determined by Monte Carlo simulation (Sec. III).

A large fraction of the background after the energy cut comes from continuum events. This is because the final states we are considering require two particles at the kinematic limit of B decay, and two-jet continuum events can easily mimic these final states. To reduce this kind of background we studied the correlation between the direction of the particles and the sphericity axis.[42] To avoid the effects of the candidate-particle pair biasing the sphericity-axis direction, they were excluded from the calculation. The distribution of the cosine of the angle θ between each final-state particle and the sphericity axis peaks strongly at large $|\cos\theta|$ for the continuum background; the Monte Carlo method predicts that it is flat for real B decay. We reject combinations if the $|\cos\theta|$ for at least one particle is greater than a value that changes from 0.55 to 0.75, depending on the mode. The mass distribution of candidates after this cut is shown in Fig. 15 for the $\pi^+\pi^-$ and $\rho^0\pi^-$ modes. The distribution for the $\Upsilon(4S)$ and for below threshold running are very similar. We note that the below threshold mass distributions are smooth and, in particular, show no sudden change around the region where a signal from B decay would be located. We therefore assume that the background contributions from the continuum under the $\Upsilon(4S)$ are also smooth.

We fitted the $\Upsilon(4S)$ distribution with a Gaussian plus a simple polynomial background. The background was constrained to be zero at the kinematic limit, $E_{\rm beam}$. The means of the Gaussians were set to the measured masses (not corrected for initial-state radiation) of the $\bar{B}^0$ and B^- mesons presented in Sec. III and the widths of the Gaussians were fixed at the value predicted by our Monte Carlo simulation. The fit provided us with an upper limit on the number of events allowed in the Gaussian peak. The curves in Fig. 16 represent the limits at 90% confidence level. The 90%-confidence-level upper limits on the number of events and the corresponding upper limits on the branching ratios are listed in Table I. To calculate the branching ratio limits, we again assume that 43% of the $\Upsilon(4S)$ decays are $B^0\bar{B}^0$ and 57% are B^+B^-.

A model by Bauer, Stech, and Wirbel[37] gives the branching ratios of various two-body B decays in terms of form factors and an unknown parameter a_1. For example, they predict

$$\bar{B}^0 \to D^{*+}\pi^- = 0.0037 a_1^2 \, |V_{cb}/0.05|^2$$

and

$$\bar{B}^0 \to \pi^+\pi^- = 0.0017 a_1^2 \, |V_{ub}/0.05|^2 \, .$$

Forming the ratio of these two equations, and using the branching ratio for $\bar{B}^0 \to D^{*+}\pi^-$ presented in Table I, we find $|V_{ub}/V_{cb}|<0.46$ at 90% confidence level. While this result is weaker than the limit from semileptonic B decay[7,8] (<0.16 at 90% confidence level), it is an entirely independent determination.

VII. CONCLUSIONS

We have determined the masses of the neutral and charged B mesons to be $5280.6\pm0.8\pm2.0$ and $5278.6\pm0.8\pm2.0$ MeV, respectively. The mass difference is $2.0\pm1.1\pm0.3$ MeV. We have measured the branching ratios of exclusive B-meson decay modes containing a D or D^{*+} and one or two charged pions and find them to be in the range of 0.2–1.0%. From investigations of the charged-particle momentum spectrum in $\Upsilon(4S)$ decay, we find the average branching ratio for B-meson decay into a D or D^* plus a charged pion to be $(0.81\pm0.16)\%$. This measurement also yields upper limits for $B\to\pi\pi^-$ and $B\to\rho\pi^-$. We also have searched for various exclusive two-body B decays which would arise from the $b\to u$ transition. Having found no signal, we set upper limits for various noncharm decay modes.

ACKNOWLEDGMENTS

We are most grateful for the diligent efforts of the CESR staff which made this work possible. This work was supported by the National Science Foundation and the U.S. Department of Energy. H. Kagan and R. Kass thank the Outstanding Junior Investigator program of the U.S. Department of Energy. K. Kinoshita thanks the Mary Ingraham Bunting Institute for support.

[1]E. H. Thorndike, Annu. Rev. Nucl. Part. Sci. **35**, 195 (1985).
[2]D. Andrews *et al.*, Nucl. Instrum. Methods **211**, 47 (1983).
[3]S. Behrends *et al.*, Phys. Rev. Lett. **50**, 881 (1983).
[4]R. Giles *et al.*, Phys. Rev. D **30**, 2279 (1984).
[5]C. Bebek *et al.*, Phys. Rev. Lett. **56**, 1893 (1986).
[6]M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[7]A. Chen *et al.*, Phys. Rev. Lett. **52**, 1084 (1984); C. Klopfenstein *et al.*, Phys. Lett. **130B**, 444 (1983).
[8]S. Behrends *et al.*, Cornell Report No. CLNS-87/78, 1987 (unpublished).
[9]S. Behrends *et al.*, Phys. Rev. D **31**, 2161 (1985).
[10]Particle Data Group, M. Aguilar-Benitez *et al.*, Phys. Lett. **170B**, 27 (1986).
[11]O. I. Dahl, T. B. Day, F. T. Solmitz, and N. L. Gould, SQUAW, Group A Programming Note No. P-126, University of California Lawrence Radiation Laboratory, Berkeley, 1968.
[12]The χ^2 cut of 3 per degree of freedom has an efficiency of roughly 85% depending on the mode (estimated by Monte Carlo simulation). Various background simulations indicate that the cut is effective in suppressing false hypothesis candidates.
[13]J. D. Jackson and D. L. Scharre, Nucl. Instrum. Methods **128**, 13 (1975).
[14]M. S. Alam *et al.*, Phys. Rev. D **34**, 3279 (1986).
[15]T. Sjöstrand, Lund University Report No. LU TP 80.3, 1980 (unpublished).
[16]Another subset of class (iii) background is the "feed across" for modes (2) and (6) which arises when the lepton from the semileptonic decay of one B and a charged pion from the decay of the other B in an event are mistaken for the two direct daughter pions of a B-meson decay. This is a nonnegligible effect due to the relatively large branching fraction for semileptonic B decay.
[17]If we were to assume that all of the candidates in Fig. 4 which fall in the expected B mass range are actually $\bar{B}^0\to D^{*+}\pi^+\pi^-\pi^-$ decays, the rate would be consistent with the branching ratio reported by the ARGUS Collaboration (Ref. 21).
[18]C. P. Singh, A. Sharma, and M. P. Khanna, Phys. Rev. D **24**, 788 (1981); Lai-Him Chan, Phys. Rev. Lett. **51**, 253 (1983); K. P. Tiwari, C. P. Singh, and M. P. Khanna, Phys. Rev. D **31**, 642 (1985); D. Y. Kim and S. N. Sinha, Ann. Phys. (N.Y.) **42**, 47 (1985).
[19]E. Eichten, Phys. Rev. D **22**, 1819 (1980); V. S. Mathur and M. T. Yamawaki, *ibid.* **29**, 2057 (1984).
[20]Beam-depolarization studies were performed (after collecting the run 1 data) to calibrate the CESR beam energy at the $\Upsilon(1S)$ resonance. See W. W. MacKay *et al.*, Phys. Rev. D **29**, 2483 (1984). The systematic error for the $\Upsilon(4S)$ mass is estimated by making small perturbations in the magnetic field strengths assumed in the algorithm used to compute the beam energy at the $\Upsilon(4S)$.
[21]ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. **185B**, 218 (1987).
[22]We calculate that the branching ratio is $(43\pm4)\%$ where the error is due to the statistical and systematic errors on the mass difference between the neutral and charged B mesons. The error does not reflect the overriding uncertainties due to using p-wave phase space rather than an alternative description.
[23]S. Ono, Acta Phys. Pol. B **15**, 201 (1984).
[24]M. S. Alam *et al.*, Phys. Rev. Lett. **58**, 1814 (1987).
[25]G. Goldhaber *et al.*, Phys. Lett. **69B**, 503 (1977). We use the value from this reference $(60^{+8}_{-15})\%$ rather than the more recent value of $(44\pm10)\%$ from M. W. Coles *et al.*, Phys. Rev. D **26**, 2190 (1982), because the latter did not assume isospin conservation among the strong decays of the D^{*+}.
[26]G. Gladding, in Proceedings of the Twenty-Second Rencontre de Moriond, 1987, edited by J. Tran Thanh Van (unpublished).
[27]R. H. Schindler *et al.*, Phys. Rev. D **24**, 78 (1981).
[28]The efficiency for mode (7) is determined by a Monte Carlo simulation in which the $\bar{B}^0$ decays according to four-body phase space. Other models tend to result in a lower upper limit for the branching ratio.
[29]The value of β_B is calculated using the $\Upsilon(4S)$ mass and the average of the charged- and neutral-B masses presented in Sec. III.
[30]The notation $\bar{B}^0\to x^\pm y^\mp$ in this paper means that the limit quoted is for the sum of the branching ratios for $\bar{B}^0\to x^+y^-$ and $\bar{B}^0\to x^-y^+$.
[31]D. Bortoletto *et al.*, Phys. Rev. D **35**, 19 (1987).
[32]Mark III Collaboration, R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 2140 (1986).

[33]Note that this result depends on the D and D^{*+} decay branching ratios used. The error indicated for the branching ratio includes statistical and systematic errors added in quadrature.

[34]F. Hussain and M. Scadron, Phys. Rev. D **30**, 1492 (1984).

[35]A. Ali, J. G. Körner, G. Kramer, and J. Willrodt, Z. Phys. C **1**, 269 (1979). An update of this work by J. G. Körner gives values about a factor of 3 smaller, in *Proceedings of the International Symposium on Production and Decay of Heavy Hadrons,* Heidelberg, 1986, edited by K. R. Schubert and R. Waldi (DESY, Hamburg, 1986), p. 279; J. G. Körner, Mainz Report No. MZ-TH/86-11, 1986 (unpublished).

[36]M. Wirbel, B. Stech, and M. Bauer, Z. Phys. C **29**, 637 (1985); M. Bauer and B. Stech, Phys. Lett. **152B**, 380 (1985).

[37]M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987). B. Stech, Heidelberg Report No. HD-THEP-86-7, 1986 (unpublished); M. Wirbel, in *Proceedings of the International Symposium on Production and Decay of Heavy Hadrons* (Ref. 35), p. 165; M. Wirbel, Dortmund Report No. DO-TH 86/11, 1986 (unpublished).

[38]H. J. Lipkin, Phys. Lett. **179B**, 278 (1986).

[39]M. G. D. Gilchriese, in *Proceedings of the Twenty-Third International Conference on High Energy Physics,* Berkeley, California, 1986, edited by S. Loken (World Scientific, Singapore 1987).

[40]F. J. Gilman and S. H. Rhie, Phys. Rev. D **31**, 1066 (1985).

[41]The mass and width of the $a_1(1270)$ produced hadronically are measured to be 1275 and 315 MeV, respectively. [See, Particle Data Group, C. G. Wohl *et al.*, Rev. Mod. Phys. **56**, S157 (1984).] However, those measured in τ decay in e^+e^- experiments have a mass around 1100 MeV [see J. A. Jaros *et al.*, Phys. Rev. Lett. **40**, 1120 (1978)], perhaps because of limited phase space for $\tau \to a_1(1270)\nu$. For a more detailed discussion, see J.-L. Basdevant and E. L. Berger, *ibid.* **40**, 994 (1978).

[42]J. D. Bjorken and S. J. Brodsky, Phys. Rev. D **1**, 1416 (1970).