PHYSICAL REVIEW D VOLUME 31, NUMBER 9 1 MAY 1985

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Observation of the decay $\bar{B}^0 \to D^{*+}\rho^-$

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(Received 28 January 1985; revised manuscript received 25 February 1985)

The decay $\bar{B}^0 \to D^{*+}\rho^-$ has been observed and the branching ratio is found to be $(8.1 \pm 2.9^{+5.9}_{-2.4})\%$. The result is compared with theoretical predictions.

All experimental evidence[1–3] accumulated up to now is consistent with a model in which B-meson decay is brought about by the decay of the b quark into a c quark (see Fig. 1). There is also evidence[2] suggesting that the virtual W boson and the remaining quark pair fragment almost independently of one another. This model has been used to predict[3–5] the branching fractions for the two-body decay modes of B mesons in much the same way that Tsai[6] calculated the hadronic branching fractions for τ decay. Here we report the first observation of the decay $\bar{B}^0 \to D^{*+}\rho^-$ and compare the branching fraction with theoretical predictions.

The $\Upsilon(4S)$ is a $b\bar{b}$ resonance that is produced in e^+e^- annihilation[7] and decays almost exclusively to $B\bar{B}$ meson pairs, thus providing an excellent means of studying these particles. The decay of B mesons into exclusive channels was first observed[8] by fully reconstructing 18 candidate events from four decay modes containing a D^0 and charged pions. Since then, we have used other methods to study some of these modes. In particular we have measured[3] the branching ratio for $\bar{B}^0 \to D^{*+}\pi^-$ to be $(1.7 \pm 0.5 \pm 0.5)\%$ using a method that does not require detection of the D^0

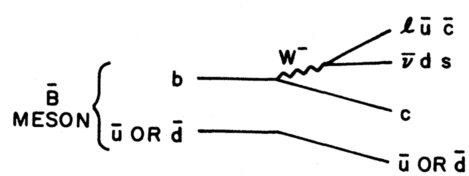

FIG. 1. The spectator decay diagram for B mesons.

produced in the decay of the D^{*+}. The same partial-reconstruction technique is used here to detect the decay $\bar{B}^0 \to D^{*+}\rho^-$.

The data come from the CLEO experiment at the Cornell Electron Storage Ring (CESR), and consist of 40.6 pb^{-1} of $\Upsilon(4S)$ data and 17.3 pb^{-1} of continuum data between the $\Upsilon(3S)$ and $\Upsilon(4S)$. In the CLEO detector the visible cross section of the $\Upsilon(4S)$ is a 1.1-nb enhancement above a 3.1-nb continuum background. Details of the detector[9] and hadronic-event-selection criteria[10] have been presented elsewhere. For this analysis we have used the cylindrical drift chamber inside a 1.0-T solenoidal magnet to determine the momenta of charged particles. To detect π^0's we used the octant shower counters, which cover $0.56\times 4\pi$ sr in solid angle and are constructed from proportional tubes interleaved with sheets of lead.

There were 170 200 hadronic events in the $\Upsilon(4S)$ data, and 54 800 in the continuum data. Scaling the number of continuum events by the luminosity ratio of the two data sets, allowing for the energy dependence of the continuum cross section, and correcting for the 91% event-selection efficiency, we get 47 800 for the total number of $\Upsilon(4S)$ decay events.

A major reduction in the background from the continuum hadronic events was achieved by rejecting events with a two jet structure; this was done by requiring that the ratio of Fox-Wolfram moments,[11] $R_2 = H_2/H_0$, be less than 0.3.

We call a photon any shower that has an energy greater than 0.25 GeV and that does not link with a drift-chamber track. The two-photon mass distribution for combinations with energy greater than 1.0 GeV is shown in Fig. 2. A clear π^0 peak is seen. Any two-photon combination with energy greater than 1.0 GeV and $0.07 < M_{\gamma\gamma} < 0.20$ GeV/c^2 is taken to be a possible π^0. For each π^0 candidate the photon energies are adjusted so as to constrain $M_{\gamma\gamma}$ to be equal to the true π^0 mass.

We wish to study the decay chain

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

and its charge conjugate (in this paper wherever we specify a decay mode we also imply its charge conjugate). We have measured[3] the $\bar{B}^0$ mass to be $5275.2 \pm 1.9 \pm 2.0$ MeV/c^2; this is 14 MeV less than the beam energy when running on

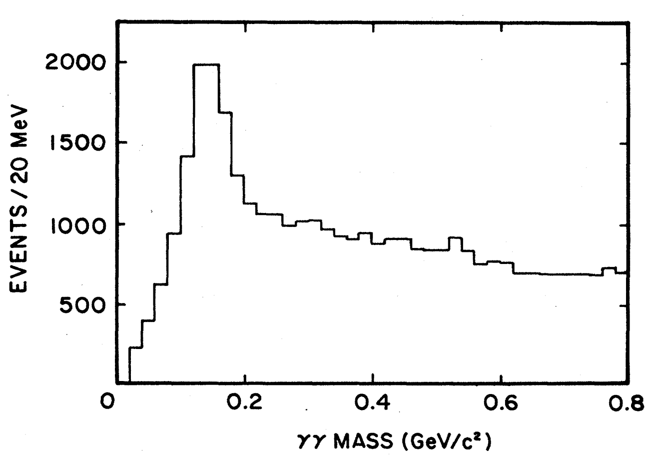

FIG. 2. The two-photon mass distribution for combinations with energy greater than 1.0 GeV.

the $\Upsilon(4S)$ resonance. Since the $\bar{B}^0$ is moving very slowly in the laboratory frame ($\beta = 0.07$) the $\pi^-\pi^0$ momentum is confined to a narrow interval for any given value of the $\pi^-\pi^0$ mass $M_{\pi\pi}$; for example, at the ρ mass (0.77 GeV/c^2) this momentum interval is 2.0–2.4 GeV/c. Furthermore, the π^+ emitted in the decay of the D^{*+} is very soft ($p < 0.23$ GeV/c) and its direction is opposite to the $\pi^-\pi^0$ direction to within 26°. We call this pion the "soft" pion.

To obtain a signal for this decay we need only detect the two charged pions in the drift chamber, along with the π^0 in the shower counter. No charged-particle identification is used, and neither do we attempt to reconstruct the D^0 from its decay products. Energy conservation demands that the energy of the $\bar{B}^0$ be equal to the beam energy $E_{\rm beam}$. Knowing the $\pi^-\pi^0$ energy $E_{\pi\pi}$, we can therefore calculate the D^{*+} energy

$$E_{D^*} = E_{\rm beam} - E_{\pi\pi} \; .$$

From the three-momentum of the soft pion, the D^{*+} energy, and the D^0 mass we can determine the angle between the D^{*+} and the soft pion. The only quantity that remains undetermined is the azimuthal angle of the D^{*+} about the soft-pion direction. For a genuine $\bar{B}^0$ decay we will be able to find an azimuthal angle that gives a reconstructed $\bar{B}^0$ mass within 14 MeV of the beam energy, whereas for the bulk of the fake combinations this will be impossible. In the following analysis we therefore take the azimuthal angle that yields the maximum computed $\bar{B}^0$ mass $M_{\rm max}$ and plot $M_{\rm max} - E_{\rm beam}$; our "signal" events should accumulate near $M_{\rm max} - E_{\rm beam} = 0$.

Figure 3 shows the distribution of $M_{\rm max} - E_{\rm beam}$ for different regions of the $\pi^-\pi^0$ invariant mass $M_{\pi\pi}$. Using the measured value of $M_{\pi\pi}$ we have demanded that the $\pi^-\pi^0$ momentum be less than the maximum kinematically allowed for the decay $\bar{B}^0 \to D^{*+}\pi^-\pi^0$, and we further demand that the $\pi^-\pi^0$ momentum be greater than the value it would have if the $\pi^-\pi^0$ system were to make an angle of 60° with the laboratory direction in the $\bar{B}^0$ rest frame; the latter cut reduces background from decays of the type $B \to D^{*+}\pi^-\pi^0(n\pi)$, where $n\pi$ represents one or more additional pions. For $M_{\pi\pi} < 2$ GeV/c^2 the acceptance for our signal events is approximately independent of $M_{\pi\pi}$.

Some peaking is seen near $M_{\rm max} - E_{\rm beam} = 0$; however, *a priori*, we have no good reason to suppose that the background should be flat in this variable. Our purpose in showing these distributions is to show the peak near $M_{\rm max} - E_{\rm beam} = 0$ and to demonstrate how well our background estimates agree with the data outside the region in which the signal is expected.

We have studied three separate background estimates: (1) same-sign combinations ($D^{*+}\pi^+\pi^0$), (2) parity reflection of the soft pion (inverting the momentum of all soft-pion condidates before forming mass combinations), and (3) $D^{*+}\pi^-\pi^+$ combinations. It might be thought that the $D^{*+}\pi^-\pi^+$ combinations would show a signal from B^+ decay; however, such decays are not favored because the D^{*+} contains a c quark, whereas B^+ decay should normally produce a $\bar{c}$ quark. To use these combinations as a background estimate we take only π^+'s that point at the fiducial volume of the shower counter, and to model the resolution of the shower counter, we smear their momenta p by $15\%/\sqrt{p}$ (p in GeV/c). The resulting $\pi^+\pi^-$ mass distribution, multiplied by a normalization factor of 0.132, describes the $\pi^0\pi^-$ mass distribution to better than $\pm 10\%$.

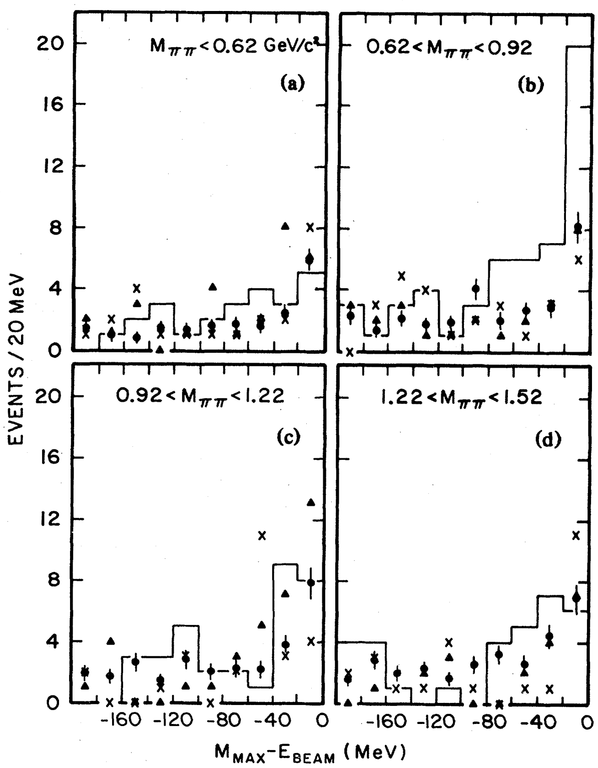

FIG. 3. The distribution of $\Upsilon(4S)$ events in $M_{\max}-E_{\text{beam}}$ for different regions of $M_{\pi\pi}$. The histrogram shows the data for the channel $\bar{B}^0 \to D^{*+}\pi^-\pi^0$ in which the signal is expected to appear. The plotted points show the three background estimates: (1) triangles, the same-sign combinations ($D^{*+}\pi^+\pi^0$); (2) crosses, the reflected soft-pion background; (3) circles, the $D^{*+}\pi^-\pi^+$ combinations, multiplied by a normalization factor of 0.132.

The three background calculations are plotted with the data in Fig. 3. Our Monte Carlo simulation predicts that the mass range $0.62 < M_{\pi\pi} < 0.92$ GeV/c^2 should contain the bulk of any signal due to the decay $\bar{B}^0 \to D^{*+}\rho^-$. By any background estimate there appears to be a significant signal for $0.62 < M_{\pi\pi} < 0.92$ GeV/c^2, but no signal in any other range of $M_{\pi\pi}$.

We assume that the signal in the mass range $0.62 < M_{\pi\pi} < 0.92$ GeV/c^2 is entirely due to the channel $\bar{B}^0 \to D^{*+}\rho^-$. In the region $M_{\max}-E_{\text{beam}} > -20$ MeV we observe a total of 20 candidates of which one must be false, as there are two candidates from one event. Our three background estimates yield, respectively, 8.0 ± 2.8, 6.0 ± 2.4, and 8.16 ± 1.04 events. We can make one more background estimate by averaging the number of events with $M_{\max}-E_{\text{beam}} > -20$ MeV in the adjacent $\pi^-\pi^0$ mass ranges; by this method we estimate a background of 6.5 ± 1.8 events. Since all four background estimates are consistent, we take the weighted average of 7.6 ± 0.8 events as our best estimate; this leaves a signal of 12.4 ± 4.5 events. The systematic error in the background has been neglected; in any case it must be small compared with the statistical error in the signal.

When the same procedure was applied to the 17.3 pb^{-1} of continuum data sample, no events were found with $M_{\max}-E_{\text{beam}} > -20$ MeV. This is consistent with the number expected from the various background-estimation methods.

We believe that our background estimates accurately account for most of the possible sources of background. In particular, the $D^{*+}\rho^0$ background [from method (3)] must give a reasonable estimate of the potentially dangerous background from $\bar{B}^0 \to D^{*-}X^-$, $X^- \to \rho^-\pi^0$, since by isospin invariance (assuming X decays strongly) X should decay equally often via $X^- \to \rho^0\pi^-$. However, we cannot altogether exclude the possibility that the decays contributing to our signal contain additional low-momentum pions; for example, any decay of the type $B \to D^{**}\rho^-$, $D^{**} \to D^{*+}\pi$ with a $D^{**}-D^*$ mass difference of 0.2 GeV/c^2 could contribute to our signal with an efficiency which is about 60% of the efficiency for the direct decay. No such D^{**} particle has ever been observed.

The detection efficiency was determined from 6400 Monte Carlo events of the type

$$e^+e^- \to B^0\bar{B}^0,\ \ \bar{B}^0 \to D^{*+}\rho^-,\ \ D^{*+} \to D^0\pi^+ \ .$$

Electromagnetic showers were propagated using the EGS Monte Carlo code;[12] the nuclear interactions of hadrons were also simulated. We have checked that when this Monte Carlo code is used to calculate the detection efficiency for inclusive π^0's, we obtain the expected result that for both continuum events and $\Upsilon(1S)$ decay, the measured π^0 momentum spectra are the same as the average of the π^+ and π^- spectra. From the Monte Carlo results we conclude that the efficiency for a $\bar{B}^0 \to D^{*+}\rho^-$, $D^{*+} \to D^0\pi^+$ event to be detected with $M_{\max}-E_{\text{beam}} > -20$ MeV is $(0.89 \pm 0.18)\%$ for the helicity-1 state and $(0.44 \pm 0.12)\%$ for the helicity-0 state; very few Monte Carlo events were found at smaller $M_{\max}-E_{\text{beam}}$. The dependence of the detection efficiency on the helicity state comes from both the π^0 energy cut and the poor efficiency for reconstructing low-momentum tracks in the drift chamber. The data are insufficient to determine whether either helicity state is perferred, so we take the efficiency to be $(0.67 \pm 0.23)\%$, where the quoted error accounts for the lack of knowledge of the helicity. The dominant factor in the efficiency is the π^0 reconstruction efficiency, which is about 5% for π^0 energies above 1.0 GeV.

The $D^{*+} \to D^0\pi^+$ branching ratio has been measured[13] as 0.60 ± 0.15. The branching ratio for the decay $\Upsilon(4S) \to B^0\bar{B}^0$ has not been measured, but has been calculated[8,14] to be 0.4 or 0.5. To be consistent with our previous publications we shall assume the former value. We therefore find

$$B(\bar{B}^0 \to D^{*+}\rho^-) = (8.1 \pm 2.9^{+5.9}_{-2.4})\% \ ,$$

where the first error is statistical and the second is systematic.

If the helicity-0 mode happens to dominate the decay our measurement puts a rather poor upper limit on the branching ratio; at 90% confidence this limit is 21%. The polarized ρ^- in a helicity-0 decay has a 22% probability to produce a charged pion with momentum in the range 1.85–2.11 GeV/c (i.e., $0.35 < p/E_{\text{beam}} < 0.40$). Simply by counting the measured number of charged tracks in this momentum interval we obtain[15] a 90%-confidence upper limit of 11% for the helicity-0 branching ratio. This assumes that the decays $\bar{B}^0 \to D^{*+}\rho^-$ and $B^- \to D^{*0}\rho^-$ have the same branching ratio.

In Ref. 3 we have predicted the sum of branching ratios,

$$B(\bar{B}^0 \to D^{*+}\rho^-) + B(\bar{B}^0 \to D^+\rho^-) = 4.9\%,$$

and Ali, Körner, Kramer, and Willrodt[4] predict the $\bar{B}^0 \to D^{*+}\rho^-$ branching ratio to be 3.0%. Our measurement is consistent with both of these predictions, but is not consistent with the value $B(\bar{B}^0 \to D^{*+}\rho^-) = 0.73\%$ predicted by Hussain and Scadron.[5] References 3 and 4 predict that the $\bar{B}^0 \to D^{*+}\rho^-$ decay rate should be 2.6 times larger than for $\bar{B}^0 \to D^{*+}\pi^-$ and Ref. 5 predicts this ratio to be 2.2. Combining the result presented here with the $\bar{B}^0 \to D^{*+}\pi^-$ measurement from Ref. 3, we find the ratio of $\bar{B}^0 \to D^{*+}\rho^-$ to $\bar{B}^0 \to D^{*+}\pi^-$ decays to be 4.7 ± 2.7, which is consistent with all predictions. The measurement of this ratio is independent of uncertainties in the branching fractions for $\Upsilon(4S) \to B^0\bar{B}^0$ and $D^{*+} \to D^0\pi^+$.

In conclusion, we have observed the decay $\bar{B}^0 \to D^{*+}\rho^-$ and have measured its branching fraction to be $(8.1 \pm 2.9^{+5.9}_{-2.4})\%$. Our measurement is consistent with two theoretical predictions[3,4] but is inconsistent with the prediction of Hussain and Scadron.[5]

We gratefully acknowledge the efforts of the CESR accelerator staff, and the financial support of the National Science Foundation and the Department of Energy.

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