B meson Decays: Recent Results from CLEO

T. Gentile
Department of Physics and Astronomy
University of Rochester
Rochester, New York 14627
U.S.A.

Abstract

The properties of B decays are briefly reviewed. The CLEO results on the exclusive B decay modes are presented and the results of a new search for $b \to u$ 2-body transitions is reported. A novel technique for "partial" B reconstruction is presented, yielding rates for the decay modes of the form $\overline{B}^o \to D^{*+}X^-$, where X is π, ρ, or F. The CLEO results on the ratio of the charged and neutral B lifetimes and the B^o-$\overline{B}^o$ mixing limit are also presented. Finally, future prospects with an enlarged data set are outlined.

Brief Review of Early Results: Most of what is known of B mesons has been learned through the study of the decays of the $\Upsilon(4S)$ meson. The $\Upsilon(4S)$, produced as a resonance in e^+e^- annihilation, is the first $b\bar{b}$ bound state which is above threshold for production of mesons with net beauty. The CLEO data set on which the following is based consists of 40.6 pb^{-1} of integrated luminosity taken on the $\Upsilon(4S)$ and 17.3 pb^{-1} taken on the continuum immediately below the $\Upsilon(4S)$. The data were taken at the Cornell Electron Storage Ring (CESR).

The examination of the leptons coming from $\Upsilon(4S)$ decays has been especially fruitful. In particular, the yield of prompt leptons provided the first evidence that the decay products of the $\Upsilon(4S)$, B mesons, carried a new flavor and were weakly decaying[1,2] CLEO has measured the average leptonic branching fractions[3] for B mesons to be: $Br(B\to e\nu X) = .120 \pm .007 \pm .004$ and $Br(B\to \mu\nu X) = .108 \pm .006 \pm .010$ where the first errors quoted are statistical and the second errors are systematic. A search for dilepton events of the form $B\to \ell^+\ell^- X$ yielded an upper limit for flavor changing neutral current decays of less than .31% at the 90% C.L.[4] The semileptonic charged multiplicity was measured to be $3.8 \pm .4$[5] Of more significance than the simple counting of leptons observed, however, are the shapes and endpoints of the lepton momentum spectra. Figure 1 shows the electron momentum spectrum observed in $\Upsilon(4S)$ decays. Studies of this spectrum have shown that the hadronic recoil mass in the decay $B\to e\nu X$ is approximately 2 GeV/c. The shapes and the endpoints of the lepton spectra imply that the ratio of $b\to u$ transitions to $b\to c$ transitions is < 4% at the 90% C.L.[6] It seems therefore an excellent approximation to assume that every b decay produces a charmed particle. The electron momentum spectrum is consistent with a hadronic system composed of 50% D and 50% D^* mesons. Using the measured semileptonic charged multiplicities of the D mesons, the calculated charged multiplicity resulting from such a mixture would be 2.52 which suggests that there is little, if any, additional fragmentation of the daughter c quark and the spectator anti-quark. Figure 2a schematically depicts the spectator decay of a B meson in which the

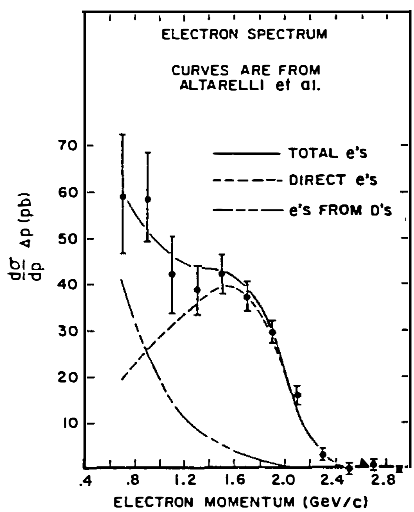

Fig. 1. Electron momentum spectrum from $\Upsilon(4S)$ decays.

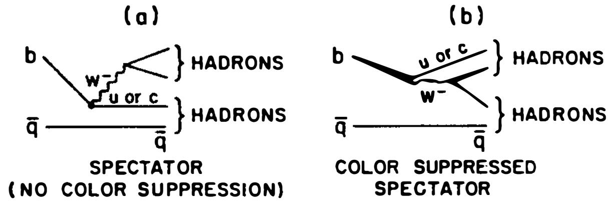

Fig. 2. Spectator decays of B mesons.

virtual W boson decay products form hadrons independent of the c quark and spectator anti-quark. Figure 2b shows a spectator decay in which one of the decay products of the W boson has the appropriate color to form a color-singlet hadron with the daughter c quark. This process is called "color-mixing". A simple argument involving the probability of producing the appropriate color anti-quark which forms a color-singlet with the daughter c quark suggests that this latter process is expected to be suppressed by approximately 1/9. Phase space calculations give a rate for $W^-\to\bar{c}s$ of ~ 15%. A search for decays of the form $B\to\psi X$ yields an upper limit for this process to be less than 1.6% at the 90% C.L.[7] in good agreement with theoretical expectations.

Figure 3 shows the observed momentum spectra of charged D^*'s and neutral D's coming from B decay. The dashed curve is a simple phase space distribution and the solid curve is obtained by using a V-A weak decay matrix element for the process $b\to ce\nu$ in which the b quark has been given the mass of the B meson and the c quark has been given the mass of the D meson. The similarity in shape between the observed momentum spectra and the $b\to ce\nu$ curve suggest that the fragmentation of the decay products of the virtual W boson emitted by the decaying b quark is nearly independent of the fragmentation of the daughter c quark and the spectator anti-quark. In summary, b decay seems well described by the spectator model with no "color mixing"; i.e. the b decays via V-A matrix element to a c quark with emmission of a virtual W boson.

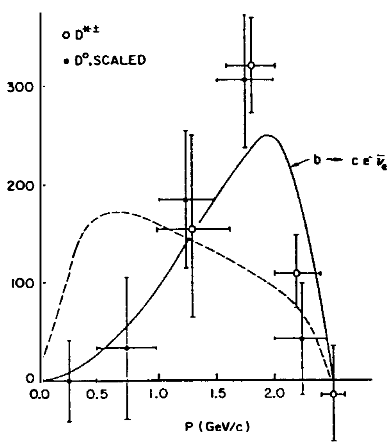

Fig. 3. D^*, D^o momentum spectra.

Full B Reconstruction: Full reconstruction[7,8] of B mesons requires the detection and correct identification of all of the decay products. This is very difficult because B mesons resulting from $\Upsilon(4S)$ decays are nearly at rest in the laboratory frame ($\beta \sim .08$) producing a nearly isotropic decay. With a mean charged multiplicity in $B\bar{B}$ events of ~ 11, the combinatorial problem of correctly choosing and identifying the right set of particles corresponding to the correct B meson decay is quite formidable. The situation becomes worse when actual acceptances and efficiencies are folded in. The most viable strategy for reconstruction of B mesons with CLEO data is to search for low multiplicity decays in which a charmed particle can be reconstructed, e.g. $B^- \to D^o \pi^- \to (K^- \pi^+)\pi^-$ or $\bar{B}^o \to D^{*+}\pi^- \to (D^o \pi^+)\pi^-$. The data were cut on the ratio of Fox-Wolfram moments[9] $H_2/H_0 = R_2 < .3$ in order to reduce the 2-jet continuum background. D^o's were made by combining identified kaons with oppositely charged tracks and required to have a momentum between 1 and 2.6 GeV/c, the kinematic maximum. Since the D^o momentum is fairly hard, the directions of its decay products are correlated with its line of flight. A cut of $|\cos\theta| < .8$ was made for the angle of the D^o daughter π with respect to the direction of the $K\pi$ system. For $K\pi$ combinations with a mass of 1865 ± 40 MeV/c^2, D^*'s were reconstructed by computing the $K\pi\pi$ - $K\pi$ mass difference, which is known to be 145.4 MeV/c^2 for the decay $D^{*+} \to D^o \pi^+$. An overall energy constraint of $m_B^2 = E_{beam}^2 + (\Sigma_i \vec{p}_i)^2$ was imposed and the 4-momenta of D^o and D^* candidates were constrained to have the correct invariant mass. Figure 4 shows the reconstruction results for events satisfying a χ^2 cut. Background estimates were made by performing the same analysis on continuum data taken below the $\Upsilon(4S)$ (no signal was observed) and by displacing the $K\pi$ mass cut ±200 MeV/c^2 from the correct D^o mass (known as the D^o side-bands). The branching fractions were computed under the assumption that the $\bar{B}^o$-B^- mass difference is Eichten's[10] theoretical value of 4.4 MeV/c^2, yielding $Br(\Upsilon(4S) \to B^o\bar{B}^o) = .40$ and $Br(\Upsilon(4S) \to B^+B^-) = .60$. The results are listed in Table I.

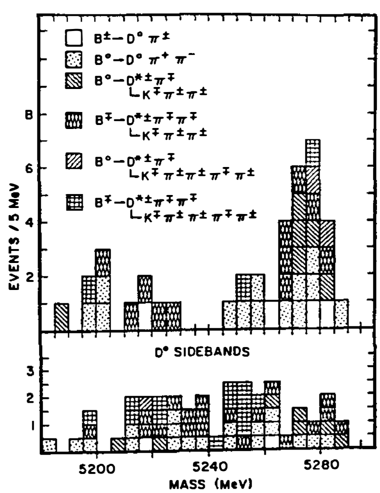

Fig. 4. B reconstruction results.

Knowledge of the B meson masses enables a precision search[7] for $b \to u$ 2-body decays such as $\bar{B}^o \to \pi^+\pi^-$ and $B^- \to \rho^o \pi^-$.

Table I

$\langle B \rangle$	$= 5273.0 \pm 1.3 \pm 2.0$ MeV/c^2	$B^- \to D^0 \pi^-$	$= (4.2 \pm 4.2)\%$
B^-	$= 5271.2 \pm 2.2 \pm 2.0$	$\bar{B}^0 \to D^0 \pi^+ \pi^-$	$= (13.0 \pm 9.0)\%$
$\bar{B}^0$	$= 5275.2 \pm 1.9 \pm 2.0$	$\bar{B}^0 \to D^{*+} \pi^-$	$= (2.6 \pm 1.9)\%$
$\bar{B}^0 - B^-$	$= 4.0 \pm 2.7 \pm 2.0$	$B^- \to D^{*+} \pi^- \pi^+$	$= (4.8 \pm 3.0)\%$

For both cases a cut was made which required the reconstructed system to be near the known beam energy within some limit: for the $\bar{B}^0 \to \pi^+ \pi^-$ case this limit was 300 MeV and for the case of $B^- \to \rho^0 \pi^-$ it was 250 MeV. A ρ^0 was defined as any $\pi^+\pi^-$ combination with invariant mass between .5 and 1 GeV. As before, the energy of the reconstructed B meson was constrained to have the beam energy. The topology of these two-body decays is quite specific. They must have two high momentum particles with invariant mass near the beam energy and yet the sum of their momenta must be relatively small: ~ 400 MeV/c. This means that they must be energetic and nearly oppositely directed in the laboratory frame, appearing much like 2-jet continuum events. The continuum background can be greatly reduced by computing the jet axis of the event without the particles comprising the B candidate. In a true $B^0\bar{B}^0$ event the other B decay should be nearly isotropic and there should be no correlation between the computed jet axis and the direction of the other B's daughter particles. However, in a 2-jet continuum event the direction of the high momentum particles, which would normally make promising B candidates, is highly correlated with the jet axis. This point is illustrated in Figure 5. In order to reduce this background, events were rejected if at least one of the high momentum particles has $|\cos\theta| > .8$ with respect to the jet axis. For the $B^- \to \rho^0 \pi^-$ case, an additional requirement was made on the polarization of the ρ^0. CLEO finds upper limits of $Br(\bar{B}^0 \to \pi^+ \pi^-) < 0.05\%$ and $Br(B^- \to \rho^0 \pi^-) < 0.06\%$ at the 90% C.L. Since the method used here is not sensitive to the mass of the final-state particles, the lepton identification capabilities of the CLEO detector can be used to set limits on processes of the form $\bar{B}^0 \to \ell^+ \ell^-$. Upper limits for these processes are $Br(\bar{B}^0 \to e^+ e^-) < 0.03\%$, $Br(\bar{B}^0 \to \mu^+ \mu^-) < 0.02\%$, and $Br(\bar{B}^0 \to e^\pm \mu^\mp) < 0.03\%$ at the 90% C.L.[7]

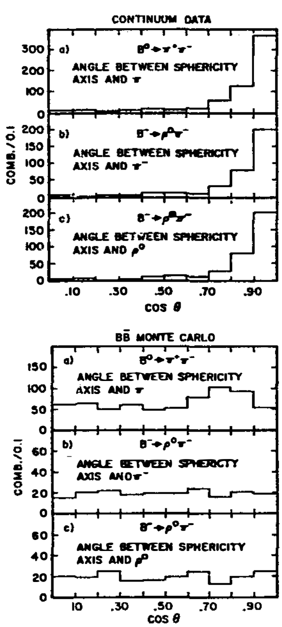

Fig. 5

Partial B Reconstruction: As evidenced in the preceeding section, full B meson reconstruction is a difficult task. From a data sample of approximately 80,000 B decays, CLEO has only been able to fully reconstruct about 25. In this section, a novel technique of "partial" B reconstruction[7] is outlined which yields measures of the branching fractions for processes of the form $\bar{B}^0 \to D^{*+}X^- \to (D^0\pi^+)X^-$, where X can be π, ρ, or F.

The word "partial" in this case refers to the fact that the D^0 is not directly observed. To illustrate the technique, consider the decay $\bar{B}^0 \to D^{*+}\pi^-$ The objective here will be to maximally exploit the particular kinematics of this decay in order to obtain an improved signal-to-background ratio. As mentioned previously, the B mesons produced in the decay of the Υ(4S) are moving very slowly ($\beta \sim .08$); therefore 2-body decays of the B meson have nearly monoenergetic spectra in the laboratory frame. In particular, the π^- momentum is constrained to lie between 2 and 2.6 GeV/c. The $D^{*+} \to D^0\pi^+$ decay has a Q value of only 145 MeV. This means that the π^+ is very soft, less than 250 MeV/c in the laboratory frame, and that it essentially retains the D^{*+} direction. Simple energy conservation gives $E_{D^0} = (E_{beam} - E_{\pi^-} - E_{\pi^+})$. This allows the calculation of the magnitude of the D^0 momentum. The angle between the D^0 and the π^+ is given by $\cos\theta = (m^2_{D^0} + m^2_{\pi^+} + 2E_{D^0}E_{\pi^+} - m^2_{D^{*+}})/(2|\vec{p}_{D^0}||\vec{p}_{\pi^+}|)$. The D^0 is thus constrained to lie on a cone around the soft π^+. The only unknown left in the problem is the angle between the D^{*+} and the π^-. This angle is chosen to maximize the reconstructed B (pseudo)mass. For a genuine $\bar{B}^0$ decay there will be an angle which yields a reconstructed $\bar{B}^0$ mass within 14 MeV of the beam energy, however this will not be possible for the bulk of the fake combinations. As seen in Figure 6, Monte Carlo studies of $B^0\bar{B}^0$ events show that this technique yields a pseudomass for the B meson which peaks between the true B mass and the beam energy. The background from 3-body decays such as $\bar{B}^0 \to D^{*+}e^-\nu$ was eliminated by requiring that the hard pion from the B decay have momentum > 2.3 GeV/c. The continuum background was reduced by requiring $R_2 < .5$. The shape of the background can

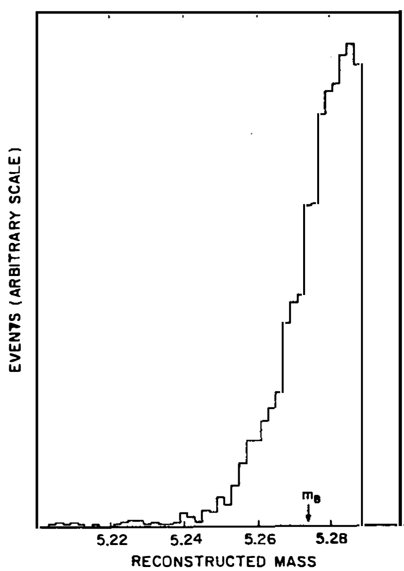

Fig. 6.

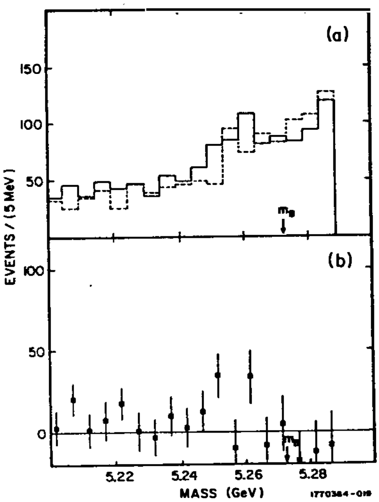

Fig. 7. (See text)

be measured in several ways. One method is to reverse the 3-momentum of the soft pion from the D^{*+} decay. The hard pion from the primary B decay and the soft pion in the D^{*+} decay should be essentially back-to-back; thus the true $\overline{B}^0$ signal should not contribute in the track-inverted analysis. Another measure of the background is the analysis of the continuum data taken below the $\Upsilon(4S)$. In this method the particle momenta are scaled by the ratio of the mass of the $\Upsilon(4S)$ and twice the actual beam energy; and in the analysis itself, the beam energy is set to be half the mass of the $\Upsilon(4S)$. Figure 7a shows the track inverted analysis on (solid) and below (dashed) the $\Upsilon(4S)$. Figure 7b shows the subtraction of the two. Figure 8a shows the partial B reconstruction pseudomass distribution (solid line) and the scaled continuum background (dashed line). Figure 8b shows the continuum subtracted signal. The analysis finds 41 ± 12 $\overline{B}^0$ events giving a value of $Br(\overline{B}^0 \to D^{*+}\pi^-)$ = (2.1 ± .5 ± .5)%, assuming $Br(\Upsilon(4S) \to B^0\overline{B}^0)$ = .4 and $Br(D^{*+} \to \pi^+ D^0)$ = .60 ± .15.[7]

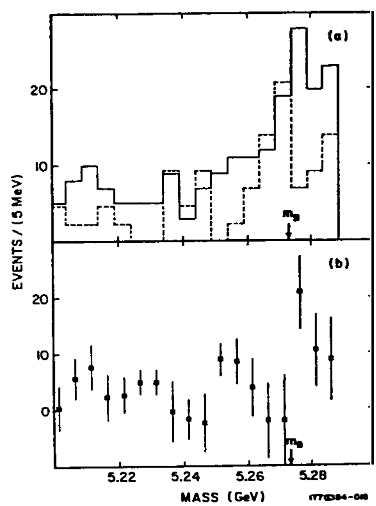

Fig. 8. (See text)

Using a similar technique[11], CLEO has measured the branching fraction for $\overline{B}^0 \to D^{*+}\rho^- \to (\pi^+ D^0)(\pi^-\pi^0)$. As in the previous example, the momentum of the ρ^- is kinematically restricted to lie between 2 GeV/c and 2.4 GeV/c. Photon showers with energies greater than 250 MeV were observed in the CLEO electromagnetic shower counters which consist of layers of proportional wire tubes interleaved with lead sheets. Pairs of showers were used to make π^0's. Figure 9 shows the

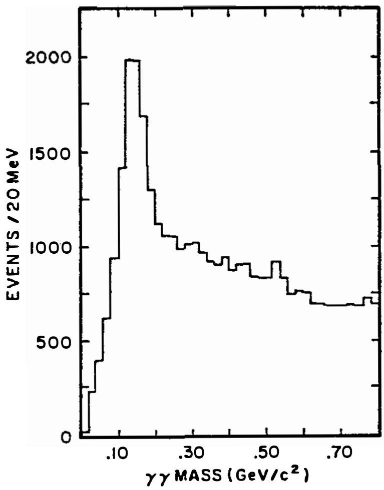

Fig. 9. γ-γ mass spectrum.

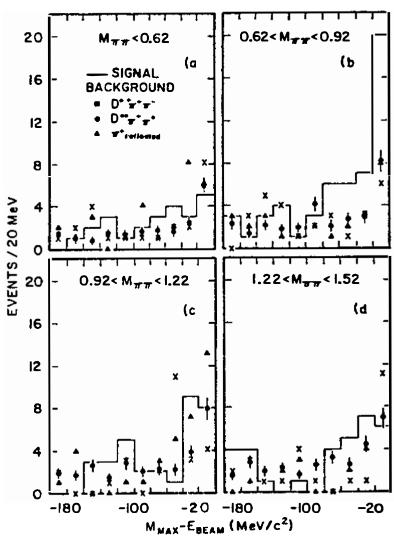

Fig. 10. Reconstructed B pseudomass.

invariant mass spectrum of photon pairs which make which make a π^o candidate with energy greater than 1 GeV. In the analysis, a π^o was defined as any photon pair with invariant mass between 70 MeV/c^2 and 200 MeV/c^2 and with energy greater than 1 GeV. The photon energies were then constrained to yield an invariant mass of m_{π^o}. The soft π^+ from the D^{*+} decay was required to have momentum of less than 230 MeV/c and its direction had to be within 26^o of the reverse ρ^- direction. The π^o candidates were paired with negatively charged tracks to make ρ^- candidates. The analysis was repeated for various ranges of the invariant mass of the $\pi^-\pi^o$ system; in each mass range the momentum of the $\pi^-\pi^o$ system was restricted to be less than the kinematic maximum allowed for $\bar{B}^o \to D^{*+}(\pi^-\pi^o)$. As before, the background from 2-jet continuum events was reduced by requiring $R_2 < .3$. The results are shown in Figure 10. A clear signal is observed for $m_{\pi^-\pi^o}$ between .62 and .92 GeV. The background was estimated in three ways: by studying the process $\bar{B}^o \to D^{*+}X^+ \to D^+(\pi^+\pi^o)$, by inverting the 3-momentum of the soft pion from the D^{*+} decay, and by studying the decay $\bar{B}^o \to D^{*+}X^o$. Subtraction of the average of the various background estimates leaves a signal of 12.4 ± 4.5 events. Under the same assumptions used in the calculation of $Br(\bar{B}^o \to D^{*}\pi^-)$, this yields $Br(\bar{B}^o \to D^{*+}\rho^-) = 7.3 \pm 2.6 ^{+9.2}_{-2.6}\%$.

The partial reconstruction technique has also been used to search for the process $\bar{B}^o \to D^{*+}F^- \to D^{*+}(\phi\pi^-)$[12]. Oppositely signed tracks not positively identified as pions were paired together under the assumption that they were kaons. The K^+K^- pairs with invariant mass within 7 MeV/c^2 of the ϕ mass were then paired with negatively charged tracks to make F^- mesons. Only F^- candidates with momentum greater than 1 GeV/c and less than 2.5 GeV/c were kept. No signal was observed, implying $Br(\bar{B}^o \to D^{*+}F^-) < 10\%$.

The Lifetime Ratio and Mixing: In semileptonic decay, only the spectator diagram contributes; thus the partial widths for $\bar{B}^o \to \ell^- \nu X^+$ and for $B^- \to \ell^- \nu X^o$ are equal. This means that the ratio of the lifetimes of the charged and neutral B mesons is equal to the ratio of the respective semileptonic branching fractions. The experimental problem for CLEO is that only the average of the semileptonic branching fractions for B mesons is measured. If the ratio of production of neutral and charged B mesons from Υ(4S) decays is taken to be 4:6 as discussed earlier, then measurements of the prompt single lepton and dilepton (from parallel B decays) yields coming from B decays can be used to unravel the average B meson leptonic branching fraction into its component parts. CLEO finds 85 $\pm$ 16 dilepton events from parallel B decays yielding a limit on the ratio of neutral to charged lifetimes of $.25 < \tau^o/\tau^- < 2.9$ at the 90% C.L.[4]

As in the K^o-$\bar{K}^o$ system, mixing between B^o and $\bar{B}^o$ is possible through the diagrams shown in Figure 11. An observable consequence of B^o-$\bar{B}^o$ mixing is the number of like sign dileptons coming from parallel B decays. A convenient parameter for measuring B^o-$\bar{B}^o$ mixing is $Y = [N(B^oB^o) + N(\bar{B}^o\bar{B}^o)]/N(B^o\bar{B}^o)$. For complete mixing Y = 1, and for no mixing Y = 0. Experimentally, Y can be related to the numbers of observed dilepton events by $Y = [N(\ell^+\ell^+) + N(\ell^-\ell^-)]/N(\ell^+\ell^-)$. Only dileptons from parallel B decays are included; fakes and cascade contributions must be subtracted out. Unfortunately, the computation of $N(\ell^+\ell^-)$ depends strongly on the production ratio of neutral to charged B mesons on the Υ(4S) and on the ratio of the semileptonic branching fractions. Figure 12 shows the 90% C.L. upper limit on Y versus the ratio of semileptonic branching fractions[4].

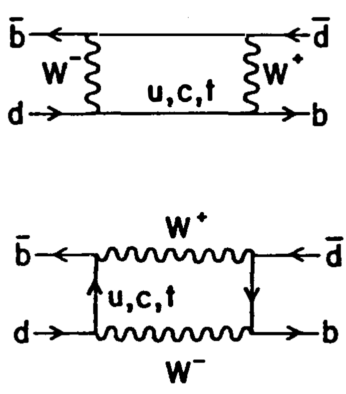

Fig. 11. B^0-$\bar{B}^0$ mixing diagrams.

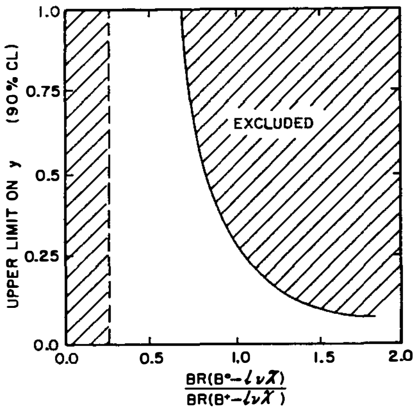

Fig. 12. Upper limit on Y.

Future Prospects: CESR has recently upgraded its LINAC to enhance its ability to produce positrons and has now moved to a seven bunch mode of operation Current running conditions now produce ~1 pb^{-1} of integrated luminosity per day at the Υ(4S) energy. The possibilities for tripling the CLEO B meson data set in 1985 are quite good. CLEO has also now added a high precision secondary vertex detector and installed charge sensitive electronics for dE/dx measurements on its main drift chamber, significantly enhancing CLEO's charged particle momentum resolution and identification abilities. With an enlarged data set, it seems feasible to: reduce the limit on b→u/b→c transitions by a factor of 4; reduce the limit on B^o-$\bar{B}^o$ mixing and the ratio of neutral to charged lifetimes by a factor of 3; perhaps measure τ_B directly; reconstruct ~ 100 additional B mesons; and improve the measured branching fractions and the B^o-B^- mass difference.

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