$B^0\bar{B}^0$ Mixing at the $\Upsilon(4S)$

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We have measured $B^0\bar{B}^0$ mixing by observing like-sign dilepton events in $\Upsilon(4S)$ decay. Assuming that the semileptonic branching fraction of the charged and neutral B mesons are equal and that the $\Upsilon(4S)$ decays to B^+B^- 55% of the time and to $B^0\bar{B}^0$ 45% of the time, we measure the mixing parameter r to be $0.19 \pm 0.06 \pm 0.06$, where the first error is statistical and the second is systematic.

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In 1987 the ARGUS Collaboration[1] reported observation of substantial $B^0\bar{B}^0$ mixing. They measured $r=0.21\pm0.08$, where r is defined as the probability that a particle created as a B^0 will decay as a $\bar{B}^0$, divided by the probability that it will decay as a B^0,

$$r=\Gamma(B^0\to\bar{B}^0\to\bar{X}^0)/\Gamma(B^0\to X^0)\,.$$

Earlier we reported[2] a 90%-confidence-level upper limit of $r<0.24$. We report here a new measurement by the CLEO Collaboration that confirms the ARGUS result. The measurement is made at the $\Upsilon(4S)$, which decays to B^+B^- or $B^0\bar{B}^0$. The signature for mixing is observation of the produced $B^0\bar{B}^0$ state decaying as B^0B^0 or $\bar{B}^0\bar{B}^0$. In e^+e^- annihilation at the $\Upsilon(4S)$, the $B^0\bar{B}^0$ is created in an odd-charge-conjugation state, for which r equals the number of $B^0B^0+\bar{B}^0\bar{B}^0$ decays divided by the number of $B^0\bar{B}^0$ decays,[3]

$$r=[N(B^0B^0)+N(\bar{B}^0\bar{B}^0)]/N(B^0\bar{B}^0)\,.$$

To measure r, we must determine whether the meson was a B^0 or $\bar{B}^0$ at the time it decayed. A convenient way of doing this is by observing the sign of the lepton charge in semileptonic decay, since in the standard model, $B^0\to l^+\nu X$ and $\bar{B}^0\to l^-\nu X$. Thus, in the absence of background processes, like-sign dileptons tag either a B^0B^0 or a $\bar{B}^0\bar{B}^0$ decay.

Measurement of r from dilepton yields, though simple in principle, is complicated by large backgrounds. We will describe how these backgrounds are determined. Finally, from the subset of like-sign dilepton events with charged kaons, we calculate r using a different method for obtaining the background. Our results are based on an integrated luminosity of 212 pb^{-1} on the $\Upsilon(4S)$ and 101 pb^{-1} from the continuum below the $B\bar{B}$ threshold. The $\Upsilon(4S)$ data include 240000 $B\bar{B}$ events.

Muon identification by CLEO has been described in detail elsewhere.[4] Electron identification has been substantially improved with the installation of a new 51-layer drift chamber operating with a 50%-50% mixture of argon-ethane gas. Specific ionization is measured with a resolution of 6.5%, providing about a 3 standard deviation separation between electrons and pions in the momentum interval of interest, 1.4–2.4 GeV/c (see below). Electromagnetic calorimeters[5] cover a solid angle of $0.47(4\pi)$. Within this solid angle and over the same momentum range, electrons are identified with 90% efficiency, while the probability of misidentifying a hadron as an electron is 0.2%. In our previous measurement,[2] the efficiency was 80% and the misidentification probability was 0.8%. For polar angles in the range $0.57<|\cos\theta|<0.8$ only the drift chamber is used. In this angular range, the electron identification efficiency is 60% (0% previously) and the hadron misidentification probability is 0.6%.

The main sources of leptons in B decay are B-meson semileptonic decay $B\to l^+\nu X$ and the sequential decay $\bar{B}\to DX$, $D\to Yl^+\nu$. In Fig. 1 we show the electron and muon spectra. Continuum and fake contributions have been subtracted and the spectrum has been corrected for efficiency. Muons with momenta less than 1.2 GeV/c are absorbed in iron and are not identified. The dashed curve is a theoretical lepton spectrum for semileptonic B decay,[6] while the solid curve is the theoretical lepton spectrum for cascade D decay. The magnitudes of the theoretical spectra are determined by fitting the electron data. The histogram is the sum of these two spectra.

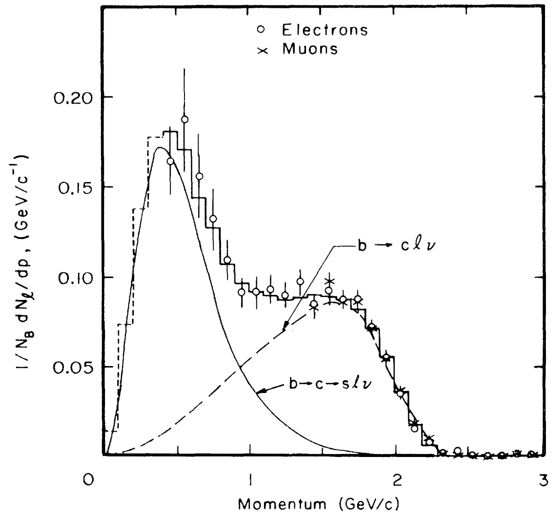

FIG. 1. Lepton momentum spectra from the $\Upsilon(4S)$. The vertical scale is the number of leptons per GeV/c per B meson. See text for a description of the curves.

We observed 15154 electrons and 9076 muons from the $\Upsilon(4S)$ between 1.4 and 2.4 GeV/c.

Dilepton events must satisfy the following requirements. (1) The angle α between the two leptons must satisfy $-0.8<\cos\alpha<0.9$. This discriminates against jetlike continuum events. (2) The momentum of each lepton must lie between 1.4 and 2.4 GeV/c. The lower limit reduces background from events in which one of the leptons comes from D decay, while the upper limit corresponds to the lepton end point from $B\to Dl\nu$ decays.

With these requirements, there remain two important sources of like-sign dilepton background: (1) "Cascades," in which one of the leptons comes from D decay and the other from B decay, so that the event contains $B\to l^+\nu X$ and $\bar{B}\to X'D\to l^+\nu Y$. (2) "Fakes," in which one of the lepton candidates is a misidentified hadron. Together these sources account for about 50% of the observed like-sign dileptons. Only 3% of the leptons in the momentum interval 1.4–2.4 GeV/c come from D decay. Nonetheless the cascades are still a large fraction of like-sign dileptons, because they arise from the decays of unmixed states of both charged and neutral B mesons which are about 10 times as frequent as decays from mixed states.

We calculate the cascade background by multiplying the measured number of single leptons from B decay by the probability of observing in the same event a lepton of momentum greater than 1.4 GeV/c from D decay. The magnitude of the lepton spectrum from D decay is obtained from our fit with the single-lepton spectrum (solid curve in Fig. 1). Only leptons from unmixed $B\bar{B}$ decays contribute to the like-sign cascade background since in the mixed case the lepton from D decay is always of opposite-sign charge to that from B decay.

The number of fake dileptons is given by $(N_l)(N_{\mathrm{tr}})p_{\mathrm{fak}}$, where N_l is the measured number of events containing a lepton; N_{tr} is the average number of tracks (other than the lepton) in these events in the appropriate momentum and angular range; and p_{fak} is the probability that a hadron will be misidentified as a lepton. p_{fak} is obtained from data taken at the $\Upsilon(1S)$, assuming that in $\Upsilon(1S)\to ggg$ decay the number of real leptons is negligible.[7] A consistent value of p_{fak} is obtained by selecting pions from K^0 decays and protons from Λ^0 decays, and determining how often we misidentify them as leptons. The uncertainty in p_{fak} is about 25%.

A small background rate that can be reliably calculated arises from events in which one B decays semileptonically and the other B decays to a ψ followed by the leptonic decay of the ψ.[8]

The observed number of dileptons and the calculated backgrounds are given in Table I. The errors in the backgrounds reflect the uncertainties in the data used to calculate them. These errors account for the systematic errors of the like-sign signals in Table I. The calculated

TABLE I. Numbers of dilepton events.

Type	Unlike sign e^+e^-	Unlike sign $\mu^+\mu^-$	Unlike sign $e^\pm\mu^\mp$	Like sign $e^\pm e^\pm$	Like sign $\mu^\pm\mu^\pm$	Like sign $e^\pm\mu^\pm$
On $\Upsilon(4S)$	186	66	218	26	6	39
Fakes	9.4 ±2.7	6.3 ±2.1	17.2 ±5.2	3.8 ±1.1	2.2 ±0.7	6.7 ±2.2
Cascades	2.0 ±0.8	0.5 ±0.2	1.9 ±0.8	10.7 ±3.2	2.6 ±0.8	10.5 ±3.2
ψ+primary lepton	0.7 ±0.3	0.3 ±0.2	1.0 ±0.5	0.7 ±0.3	0.3 ±0.2	1.0 ±0.5
Continuum background	6.5 ±4.2	2.4 ±3.0	−3.7 ±1.3	None (see text)		
Signal	167	57	202	10.8	0.9	20.8
statistical	±14	±8	±15	±5.1	±2.4	±6.2
systematic	±2.8	±2.1	±5.3	±3.4	±1.1	±3.9

$\Upsilon(4S)$ fake background includes continuum fakes and, therefore, we have removed the fakes from the continuum background; thus the continuum background represents only real dileptons. Since D mixing is small, all observed like-sign dileptons from the continuum are caused by fakes and so there is no like-sign continuum background. A total of 71 like-sign dileptons were observed, of which 38.5 are estimated to be background, and 32.5 ± 8.4 are signal (statistical error only). The comparable numbers from ARGUS are 50 total, 25.2 background, and 24.8 ± 7.6 signal.[1]

The mixing parameter r is calculated from the numbers in the "signal" row of Table I. The like-sign dileptons, N_{++} and N_{--}, come from events with two neutral B's. The unlike-sign dileptons, N_{+-}, include contributions from B^+B^- decay which must be subtracted from the total number. The mixing parameter is given by

$$r=(N_{++}+N_{--})/[N_{+-}-N_{+-}(\text{from } B^+B^- \text{ decay})] .$$

The number of opposite-sign dileptons from B^+B^- decay can be determined from the ratio of the charged- to neutral-B-meson semileptonic branching fractions, b_+/b_0, and from the ratio of charged to neutral B's in $\Upsilon(4S)$ decay, f_{+-}/f_{00} $(f_{+-}+f_{00}=1)$:

$$N_{+-}(\text{from } B^+B^- \text{ decay})=\frac{b_+^2 f_{+-}}{b_+^2 f_{+-}+b_0^2 f_{00}}(N_{+-}+N_{++}+N_{--})=\Lambda_{+-}(N_{+-}+N_{++}+N_{--}) .$$

Neither b_+/b_0 nor f_{+-}/f_{00} is well known. The current experimental limits[2,9] are approximately 0.5–2.0 and 1.0–1.5, respectively. For comparison with the ARGUS result,[1] we take $\Lambda_{+-}=0.55$.

Since the detection efficiencies for ee, $\mu\mu$, and $e\mu$ events are not identical, we calculate r separately for each set of particles and average them. The results are $r_{ee}=0.158\pm0.085\pm0.056$, $r_{\mu\mu}=0.036\pm0.098\pm0.062$, and $r_{e\mu}=0.262\pm0.088\pm0.051$. Note that the value of $r_{\mu\mu}$ is low. This is not due to an inefficiency in muon detection as evidenced by the fact that the number of opposite-sign dileptons is consistent with that expected from the observed single-muon rates. We calculate a weighted average $r=w_{ee}r_{ee}+w_{\mu\mu}r_{\mu\mu}+w_{e\mu}r_{e\mu}$, where the weights w_{ee}, $w_{\mu\mu}$, and $w_{e\mu}$, respectively, 0.38, 0.15, and 0.47, are proportional to the expected number of dileptons, calculated from the single-lepton rates. We obtain $r=0.188\pm0.055\pm0.056$ for the weighted average. The statistical errors have been combined in quadrature and the systematic errors have been combined linearly. We have checked that the mixing result is not sensitive to our minimum-momentum cut, $p_l>1.4$ GeV/c, by varying this cut from 1.3 to 1.6 GeV/c.

The errors quoted for r do not include the uncertainty in Λ_{+-}. Since a change in the value of Λ_{+-} changes only the number of unlike-sign dileptons, it will not affect the statistical significance of the result, which is determined by the number of like-sign dileptons. Within the present experimental limits for b_+/b_0 and f_{+-}/f_{00}, Λ_{+-} can vary from 0.20 to 0.85. For $\Lambda_{+-}=0.85$, one finds almost complete mixing $(r\sim1)$. For $\Lambda_{+-}=0.20$, $r=0.101\pm0.027\pm0.028$. Thus, for any value of Λ_{+-} consistent with experimental data, the mixing is large.

We can measure the mixing parameter r by a different method using like-sign dilepton events that have an observed charged kaon. The ratio of mixed to background events in this sample is determined from the fraction, f, of these events in which the kaon has the same-sign charge as the two leptons. For a pure sample of mixed events $f=0.87\pm0.10$ and for fake and cascade background events $f=0.42\pm0.03$.[10]

We find 25.7 like-sign dileptons with identified charged kaons of which 17.2 have the same-sign charge as the leptons and 8.5 the opposite sign, leading to $f=0.67\pm0.09$. We also find 142 ± 13 unlike-sign dileptons with an identified charged kaon. Using these numbers we find $r=0.29\pm0.15\pm0.08$. Though of less statistical power than the full sample, this provides an independent determination of the ratio of signal-to-background events and serves as a check on the background calculation in the full like-sign dilepton sample. However, since the two measurements are correlated, we have not combined them.

Our value of r from the full dilepton sample translates into $\Delta M/\Gamma=0.69\pm0.12\pm0.12$,[3] where ΔM is the mass difference between the weak eigenstates and Γ is their mean decay width.

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[10] The value of f for mixed events is less than 1 because some fraction of the time the D's decay to the "wrong"-sign kaon. Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 1 (1988). For background events f is determined to be 0.42 ± 0.03. See R. Kowalewski, Cornell University Report No. CLNS 89/890, 1989 (to be published).