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Upper Limit on $B^0\bar{B}^0$ Mixing in e^+e^- Annihilation at 29 GeV*

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The rate of dilepton production in the process $e^+e^- \rightarrow$ hadrons at $\sqrt{s} = 29$ GeV is found to be in good agreement with predictions based on semileptonic decays of bottom and charm hadrons. We determine that the average probability for a semileptonic decay of a hadron initially containing a b quark to produce a positive lepton is less than 0.12 at the 90% confidence level and set upper limits on $B^0\bar{B}^0$ mixing.

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New knowledge of the weak mixing angles, imposed by the long B lifetime[1,2], a lower bound on the t quark mass[3], and a small ratio[4] of $\Gamma(b \to u)/\Gamma(b \to c)$, has led to predictions that B_s^0 mesons and, to a much lesser extent, B_d^0 mesons should exhibit mixing[5]. $B^0\bar{B}^0$ mixing can lead to the production of like-sign dileptons in the process $e^+e^- \to B^0\bar{B}X \to \bar{B}^0\bar{B}X \to \ell^-\ell^-X$[6]. Recently, the CLEO collaboration[7] has reported an upper limit on $B_d^0\bar{B}_d^0$ mixing from the rate of like-sign dileptons produced in the decay of the $\Upsilon(4s)$. The UA1 collaboration[8] has observed like-sign dimuon events, leading to speculations in the literature[9] that these events could arise from $B_s^0\bar{B}_s^0$ mixing. In this Letter, we report a measurement of dilepton rates in e^+e^- annihilation at an energy above the B_s^0 production threshold.

The data, collected with the MARK II detector at the electron-positron storage ring PEP, correspond to an integrated luminosity of 220 pb^{-1} at a center-of-mass energy E_{cm} of 29 GeV. The MARK II detector has been described elsewhere[10], and we mention here only the elements essential to this analysis. Charged particle momenta are measured over 76% of the full solid angle with a cylindrical drift chamber in an axial magnetic field. The rms momentum resolution is $(\delta p/p)^2 \simeq (0.025)^2 + (0.010p)^2$, where the momentum p is in units of GeV/c. Electrons are identified over 64% of the full solid angle with a lead-liquid-argon calorimeter. Muon identification is accomplished over 45% of the full solid angle with four layers of proportional wire chambers separated by iron hadron absorbers.

We select hadronic events with a total energy greater than $E_{cm}/4$, and which contain at least five charged particles with momenta greater than 100 MeV/c.

Events are retained if the polar angle θ of the thrust axis satisfies $|\cos\theta| < 0.7$. There are 72535 hadronic events selected. We estimate the total background in this sample from τ production, beam-gas collisions, and two-photon processes to be $(3.0 \pm 1.0)\%$. The lepton selection criteria have been described elsewhere[2,11]. Electron identification is based on a comparison of the energy deposition in three groupings of layers in the calorimeter with the momentum measured in the drift chamber. Muons are identified as those particles whose extrapolated trajectories coincide, within multiple Coulomb scattering errors, with hits in all four proportional tube planes of the muon system. The transverse momenta p_t of the leptons are determined relative to the thrust axis of the event. To eliminate a background to the lepton signal from the two-photon process $e^+e^- \to e^+e^- +$ hadrons with one or both of the electrons scattered into the calorimeter, we reject events in which there is a lepton with a momentum p above 10 GeV/c, or a transverse momentum p_t above 2.5 GeV/c, or in which the lepton is isolated by more than 90° from the nearest charged track in the plane perpendicular to the beam direction.

We classify the leptons into two kinematic regions dominated by bottom and charm decay. Leptons in the kinematic region of $p > 2$ GeV/c and $p_t > 1$ GeV/c comprise the *bottom* enriched lepton sample; those in the kinematic region of $p > 3$ GeV/c and $p_t < 1$ GeV/c the *charm* enriched sample. In the b-enriched (c-enriched) region, we observe 574 (1159) electron candidates and 362 (570) muon candidates. Dilepton events in this analysis are defined to be those events with exactly two lepton candidates in the combined kinematic regions described above. In Table 1, we group the dilepton events according to kinematic regions of the two lepton candidates, whether the leptons are in the same or opposite jet (defined by the plane normal to the thrust axis), and whether they have the same or opposite charge. In the combined kinematic regions, we observe 40 unlike-sign and 9 like-sign dileptons in opposite jets.

We compare the observed number of dilepton events with predictions based on the semileptonic decay of particles containing b and c quarks. In a separate analysis, we have studied the momentum and transverse momentum spectra of inclusive leptons[11]. In the two kinematic regions described above, we determine the relative amounts of leptons that originate from primary b, primary c, secondary c decay ($b \to c \to \ell$), and from background sources (misidentified hadrons and non-prompt leptons). The fractions of electron and muon candidates from these sources are given in Table 2 for the *bottom* and *charm* enriched regions. Based on these fractions from the inclusive lepton analysis, we calculate the expected numbers of dilepton events which are summarized in Table 1. The fractions of unlike-sign dileptons in opposite jets that arise from two primary B decays are 0.91 if both lepton candidates are in the b-enriched sample, 0.72 if one lepton candidate is in the b-enriched sample and one in the c-enriched sample, and 0.34 if both lepton candidates are in the c-enriched sample. We find the observed rate of dileptons completely consistent with expectations from heavy quark decay without taking mixing into account. In particular, the relative rates of like and unlike-sign dileptons, same and opposite jet dileptons, and ee, eμ, and $\mu\mu$, are in good agreement with predictions.

In order to include mixing effects in our predictions, we define a probability $\chi = \Gamma(B \to \ell^- X)/\Gamma(B \to \ell^\pm X)$ that a B hadron initially containing a $\bar{b}$ quark decays into a negative lepton, where Γ is the total time-integrated rate. In the definition of χ, we average over all types of B hadrons, both mesons and baryons produced at our energy. If the predicted dilepton rate from two primary B decays is denoted by $N_{2\ell}$, the expected rate for opposite and same charge combinations is $N_{+-} = ((1-\chi)^2 + \chi^2)N_{2\ell}$ and $N_{\pm\pm} = 2\chi(1-\chi)N_{2\ell}$, where it is assumed that the two types of B hadrons produced by b and $\bar{b}$ hadronization are uncorrelated. Furthermore, it is assumed that the B hadrons undergo mixing without interference[12]. The mixing parameter χ is varied in a log likelihood fit, and the predicted numbers of like and unlike-sign dileptons from all sources are fit to the observed events. Since mixing does not affect dileptons in the same jet, we include only dileptons in opposite jets. We fit to six bins according to kinematic region and relative lepton charge. For the case in which the fractions are fixed at the nominal values (see Table 2), the mixing probability χ is found to be consistent with zero and is less than 0.08 at the 90% confidence level.

Backgrounds to a possible mixing signal of like-sign dileptons in opposite jets arise from secondary decays ($b \to c \to \ell^+$ and $\bar{b} \to \ell^+$) and from misidentified hadrons and non-prompt leptons. The values of the secondary c decay fractions and background fractions can be checked by comparing the predicted number of unlike-sign dileptons in the same jet with observation. Slightly more than half of this predicted number is from cascade decay ($b \to \ell c X$ followed by $c \to \ell X$). The remainder is from events in which at least one lepton candidate is from a background source. Our prediction of (11.7 ± 3.1) events with unlike-sign dileptons in the same jet agrees well with the observation of 13 such events.

We have studied several sources of systematic errors, including uncertainties in the fractions from the inclusive lepton analysis, sensitivity to the p_t of the leptons due to uncertainties of the thrust axis, sensitivity to event and track selection criteria, uncertainties in the overall normalization of predicted dilepton events, and possible background to the unlike-sign dileptons from vector meson decays. A fit in which we allow the fractions in Table 2 to vary independently within their errors leads to a mixing limit of $\chi < 0.12$ (90% C.L.). This limit accommodates all systematic variations as described above.

The mixing parameter χ determined in this analysis is an average over all produced B hadron species, charged and neutral. We expect mixing to occur only for B_d^0 and B_s^0, and define mixing parameters for these neutral mesons to be $\chi_{d(s)} = \Gamma(B^0_{d(s)} \to \ell^- X)/\Gamma(B^0_{d(s)} \to \ell^\pm X)$. They are related to our measured value χ by

$$\chi = \frac{(\mathrm{BR})_\mathrm{d}}{<\mathrm{BR}>} p_d \chi_d + \frac{(\mathrm{BR})_\mathrm{s}}{<\mathrm{BR}>} p_s \chi_s$$

where p_d and p_s are the fractions of B_d^0 and B_s^0 meson production in b quark fragmentation, $(\mathrm{BR})_\mathrm{d}$ and $(\mathrm{BR})_\mathrm{s}$ are the individual semileptonic branching ratios, and $<\mathrm{BR}>$ is the average of the semileptonic branching ratios of all charged and neutral bottom hadrons weighted by their production rates. Under SU(3) flavor symmetry, the three types of B mesons would be produced in equal proportions, but with typical s quark mass suppression seen in the production of strange particles[13], the fraction of B mesons containing an s quark is expected to fall between 0.1 and 0.2 at $\sqrt{s} = 29$ GeV. Production of bottom baryons lowers the fraction of neutral B mesons. The sensitivity to mixing also depends on the semileptonic branching ratios of the different types of B mesons. These are expected to be almost equal in spectator models, but could be significantly different as is the case for D mesons.

It is more common to describe mixing in terms of the Pais and Treiman[14] parameters $r_{d(s)} = \Gamma(B^0_{d(s)} \to \ell^- X)/\Gamma(B^0_{d(s)} \to \ell^+ X)$ which are related to our variables as $r_{d(s)} = \chi_{d(s)}/(1-\chi_{d(s)})$. We give upper limits on r_d and r_s for $B^0_d\bar{B}^0_d$ and $B^0_s\bar{B}^0_s$ mixing in Fig. 1 for various values of p_d and p_s with the assumption that the semileptonic branching ratios of all B hadrons are the same. While our result does not have enough sensitivity to provide any information about $B^0_s\bar{B}^0_s$ mixing, it confirms the CLEO result of less than full $B^0_d\bar{B}^0_d$ mixing under the assumption of equal semileptonic branching ratios.

In summary, we have shown within the sensitivity of our experiment that the rate of dilepton production is consistent with expectations from heavy quark decay without mixing. Experimentally, we find that the average probability for a semileptonic decay of a hadron initially containing a b quark to produce a positive lepton is less than 0.12 at the 90% confidence level. We set upper limits on $B^0\bar{B}^0$ mixing which depend on assumptions about production rates and semileptonic branching ratios. We would like to thank F.Gilman and T.Hansl-Kozanecka for useful discussions.

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mesons are denoted by $B_d^0 = \bar{b}d$ and $B_s^0 = \bar{b}s$.

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The CLEO collaboration has set an upper limit on the dilepton ratio $y_{B_d^0} = (N_{B_d^0 B_d^0} + N_{\bar{B}_d^0 \bar{B}_d^0})/N_{B_d^0 \bar{B}_d^0} = N^{\pm\pm}/N^{+-}$. The limit set is $y_{B_d^0} < 0.30$ at the 90% CL under the assumption of equal semileptonic branching ratios. Since the B mesons are in an $\ell = 1$ state, mixing is suppressed by interference effects (see Ref. [12]) and $y_{B_d^0} = r_d$, where $r_d = \Gamma(B_d^0 \to \ell^- X)/\Gamma(B_d^0 \to \ell^+ X)$.

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Table 1

Detected (predicted) dilepton events grouped according to kinematic region, jet, and relative charge. The predictions are based on the nominal fractions given in Table 2 and do not include mixing effects. The quoted errors are estimates of the systematic uncertainties.

Kinematic Regions	Opp. Jet Opp. Sign	Opp. Jet Same Sign	Same Jet Opp. Sign	Same Jet Same Sign
both b-enriched	10 (10.0 ± 2.0)	4 (2.5 ± 0.7)	4 (2.5 ± 0.8)	0 (0.5 ± 0.1)
b-enriched & c-enriched	17 (16.8 ± 5.3)	3 (5.9 ± 1.5)	5 (5.5 ± 1.5)	0 (2.3 ± 0.6)
both c-enriched	13 (11.8 ± 3.2)	2 (4.2 ± 1.0)	4 (3.7 ± 0.9)	2 (2.4 ± 0.6)
Total	40 (38.6 ± 10.3)	9 (12.6 ± 3.2)	13 (11.7 ± 3.1)	2 (5.2 ± 1.3)

Table 2

The fractions of leptons originating from primary b decay (f_b), primary c decay (f_c), secondary c decay ($f_{c'}$), and from background sources (f_{bg}). The b-enriched and c-enriched regions are described in the text.

Region		f_b	f_c	$f_{c'}$	f_{bg}
b-enriched	e	$.58 \pm .08$	$.13 \pm .08$	$.06 \pm .03$	$.23 \pm .08$
	μ	$.51 \pm .08$	$.11 \pm .08$	$.06 \pm .03$	$.32 \pm .08$
c-enriched	e	$.20 \pm .08$	$.40 \pm .08$	$.03 \pm .015$	$.37 \pm .08$
	μ	$.20 \pm .08$	$.40 \pm .08$	$.03 \pm .015$	$.37 \pm .08$

Figure Caption

Fig.1. Limits on $B_d^0\bar{B}_d^0$ and $B_s^0\bar{B}_s^0$ mixing expressed in terms of $r_{d(s)} = \Gamma(B_{d(s)}^0 \to \ell^- X)/\Gamma(B_{d(s)}^0 \to \ell^+ X)$. The hatched area is excluded by this analysis at the 90% confidence level. Upper limits are shown for several values of p_d and p_s which are described in the text: (a) $p_d = 0.35$, $p_s = 0.10$, (b) $p_d = 0.375$, $p_s = 0.15$, (c) $p_d = 0.40$, $p_s = 0.20$. Also shown is the upper limit given by the (d) CLEO collaboration, Ref. [7]. It is assumed that all types of B hadrons decay with the same semileptonic branching ratios.

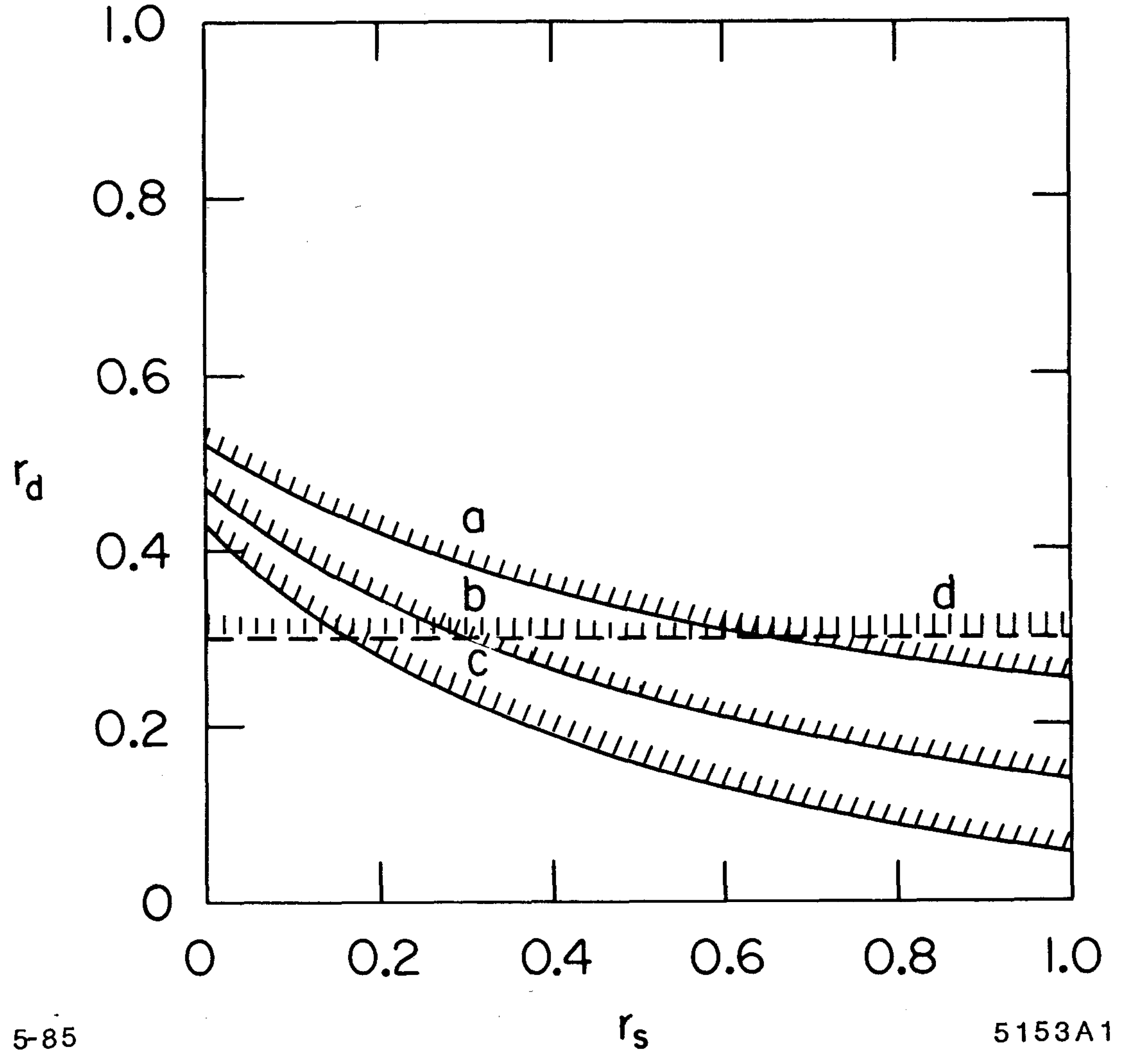

Fig. 1