Where Are the $B\bar{B}$ Mixing Effects Observable in the Υ Region?

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We estimate the B_d-$\bar{B}_d$ and B_s-$\bar{B}_s$ mixing effects using computed production cross sections for $B_q\bar{B}_q$, $B_q\bar{B}_q^*$ + c.c., $B_q^*\bar{B}_q^*$ ($q = d,s$) in the region from $\Upsilon(4S)$ to $\Upsilon(7S)$. It is shown that the mixing signal of same-sign leptons will peak at $\Upsilon(5S)$ under the assumption of standard model estimates, and if the total integrated luminosity of 1000 pb^{-1} is achieved, it will be observable.

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With the unusually long lifetime of the B meson (~ 1 psec), it is likely that B-meson physics will be a revival of the K-meson physics, which has been a great source of inspiration during the past twenty years. Among many interesting phenomena, the first step is the search for B_q-$\bar{B}_q$ mixing[1] ($q = d$ or s), which is already under way at the Cornell Electron Storage Ring (CESR), at the DESY and SLAC storage rings PETRA and PEP, and at the $p\bar{p}$ collider. At present, no meaningful bound is available from e^+e^- colliding-beam machines. The interpretation of data from $p\bar{p}$ collider experiments is much more difficult.

With planned improvements in luminosity of the machine and of the efficiency of the detectors at CESR, it is interesting to spell out clearly the expected B^0-$\bar{B}^0$ mixing effect on the basis of the standard model.

The production of $B\bar{B}$ near threshold makes the study of mixing at CESR unique and complementary to those at other laboratories. The $B\bar{B}$ and $B^*\bar{B}^*$ production lead to (after γ emission) odd-angular-momentum (L) final BB states, whereas $B\bar{B}^*$ + c.c. leads to even-L BB final states. This is an important distinction as Bose-Einstein statistics plays an important role in the mixing.[2] The production cross sections of B_s and B_d vary strongly in the CESR energy region. As B_s-$\bar{B}_s$ mixing is expected to be much larger than B_d-$\bar{B}_d$ mixing, the choice of beam energy is crucial for the mixing studies.

Cognizant of these points, we have studied the expected effects of $B\bar{B}$ mixing in the energy region between the $\Upsilon(4S)$ and $\Upsilon(7S)$.

Mixing parameters.[3]—The mixing is governed by the B^0-$\bar{B}^0$ mass matrix and more specifically by the parameter $x = 2\Delta m/\Gamma$, which is the ratio of the meson lifetime to the time required for mixing. The estimated values of x_d and x_s (standing for B_d and B_s, respectively) can be expressed in terms of the constants β_d and β_s:

$$x_d = \beta_d \times (0.05\text{–}0.2),\qquad x_s = \beta_s \times (1.6), \tag{1}$$

which are in turn estimated to be

$$\beta_d = 1,\ 0.40,\ 0.32,\ 0.33,\qquad \beta_s = 1,\ 0.54,\ 0.54,\ 0.48, \tag{2}$$

for the vacuum-saturation approximation, harmonic-oscillator model, relativistic harmonic-oscillator model, and bag model, respectively.

One expects that the potential-model description for the B meson should be better than for the K meson because of the large b-quark mass. Therefore, the β

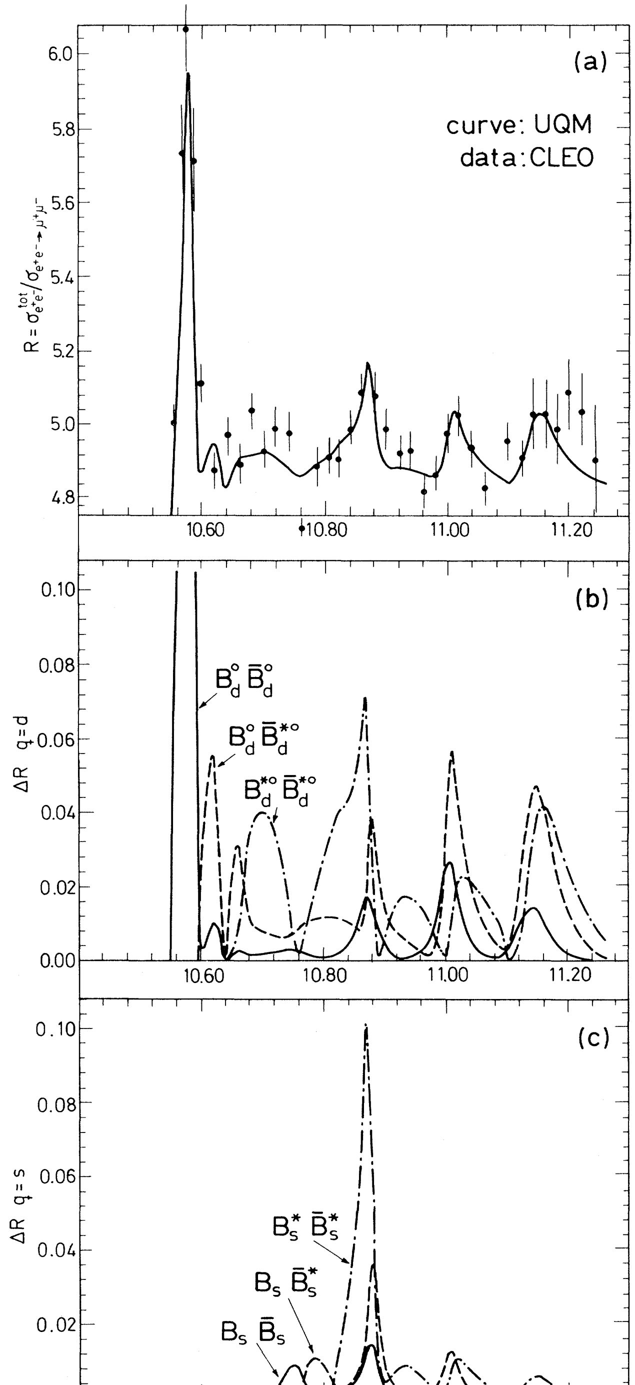

FIG. 1. (a) Data on R from CLEO (Ref. 7) compared with the UQM. (b) Contribution to $R\,(\Delta R)$ from the nonstrange neutral channels of Eq. (4) as predicted by the UQM. The solid curve is $B_d\bar{B}_d$, the dashed curve B is $B_d\bar{B}_d^* +$ c.c., and the dot-dashed curve is $B_d^*B_d^*$. (c) ΔR from the strange channels of Eq. (4) $(q=s)$. The solid curve is $B_s\bar{B}_s$, the dashed curve is $B_s\bar{B}_s^* +$ c.c., and the dot-dashed curve is $B_s^*\bar{B}_s^*$.

parameter of B_q is not strongly model dependent.

A signal of B_q-$\bar{B}_q$ mixing would be the observation of dileptons of the same sign as expected from the chain

$$e^+e^- \to B_q^0\bar{B}_q^0 + X, \quad B_q^0 \to \mu^-\bar{\nu}_\mu Y, \quad \bar{B}_q^0 \to \mu^-\bar{\nu}_\mu Y \tag{3}$$

or the charge-conjugate reaction. Obviously, $\mu^-\bar{\nu}_\mu$ can be replaced by $e^-\bar{\nu}_e$. The first thresholds of interest are

$$B_q\bar{B}_q, \quad B_q\bar{B}_q^* + \text{c.c.}, \quad B_q^*\bar{B}_q^* \quad (q=d,s). \tag{4}$$

The probability of same-sign dilepton events produced per initial $B_q\bar{B}_q$ pair depends on L as[2]

$$P_{s,1} \equiv \tfrac{1}{4}(N_q^{++}+N_q^{--})_{l=\text{odd}} = \frac{1}{2}\frac{X_q^2}{1+X_q^2},$$
$$P_{s,0} = \tfrac{1}{4}(N_q^{++}+N_q^{--})_{l=\text{even}} = \frac{1}{2}\frac{3X_q^2+X_q^4}{(1+X_q^2)^2}. \tag{5}$$

For all values of x_q, $P_{p,0} > P_{q,1}$. This suppression of P_q for odd L compared to even L follows from the Bose statistics which forbids having B_qB_q or $\bar{B}_q\bar{B}_q$ for odd L at any instant of time.

It is convenient to define the signal as the same-sign dilepton cross section divided by the $e^+e^- \to \mu^+\mu^-$ cross section and the square of the semileptonic

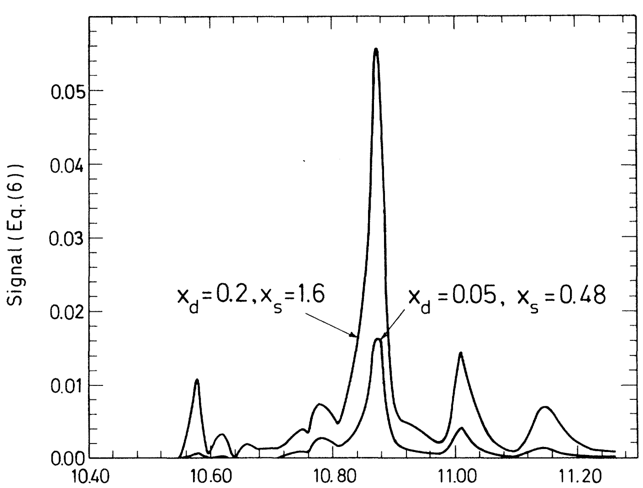

FIG. 2. Predicted signal [Eq. (6)] with use of the UQM for an optimistic and pessimistic choice of x_q values (see text) and $R_d = R_s$.

branching ratio of $B_s(R_s)$:

$$S=\frac{\sigma^{++}+\sigma^{--}}{\sigma_{\mu^+\mu^-}R_s^2}$$
$$=\left(\frac{R_d}{R_s}\right)^2\left[\Delta R(B_d\bar{B}_d+B_d^*\bar{B}_d^*)P_{d,1}+\Delta R(B_d\bar{B}_d^*+\text{c.c.})P_{d,0}\right]$$
$$+\left[\Delta R(B_s\bar{B}_s+B_s^*\bar{B}_s^*)P_{s,1}+\Delta R(B_s\bar{B}_s^*+\text{c.c.})P_{s,0}\right]. \quad (6)$$

Currently, there is no detailed knowledge of the individual leptonic branching ratios R_q of the B_q mesons. In principle, the ratio $(R_d/R_s)^2$ can range, say, from 0.5 to 2.

Considerable efforts have been put into the understanding of B-meson production [Eq. (4)] between the $\Upsilon(4S)$ and $\Upsilon(7S)$. We have studied several models[4,5] and present here the results within the unitarized quark model (UQM).[4] The UQM is a coupled-channels model which was used previously to describe the Υ's up to $4S$ (and $3D$). It was now extended to include thirteen resonances up to $7S$ and $5D$, and it involves a considerable amount of theoretical input (conventional bb potential model, the ${}^3P_0$ model for three-point functions,[6] unitarity and analyticity) and has in principle very few adjustable parameters (mainly γ_{QPC}, the quark-pair-creation strength parameters). The details will be presented in a forthcoming paper. In Fig. 1(a) we compare our model with measurements[7] of R. For the quantity S in Eq. (6), we need the contributions to R from the channels of Eq. (4), which are shown in Figs. 1(b) and 1(c). The result for S is shown in Fig. 2 with use of $R_s/R_d=1$, and for a "most pessimistic" choice of $x_d=0.05$ and $x_s=0.48$ and for a "most optimistic" choice of $x_d=0.2$ and $x_s=1.6$.

The peak observed in Fig. 2 near the $\Upsilon(5S)$ is dominated by $B_sB_s^*$ at $\sqrt{s}=10.87$ GeV. For this reason, the peak value of S varies very little ($<1\%$) for $0.5<(R_d/R_s)^2<2$.

Background.—Measurements of S at $\Upsilon(4S)$ and $\Upsilon(5S)$ are sensitive to B_d-$\bar{B}_d$ mixing and B_s-$\bar{B}_s$ mixing, respectively, and they are complementary. The signal-to-noise ratio at $\Upsilon(4S)$ has been studied by Fridman and Schwarz[8] with encouraging results. A major source of equal-sign dilepton background is the secondary D leptonic decay $B\to DY\to l\nu+Y+X$. We point out that

$$S(5S)>S(4S),\quad \Delta R(5S)<\Delta R(4S);$$

both of these inequalities help to increase the signal-to-noise ratio at $\Upsilon(5S)$ compared to that of $\Upsilon(4S)$.

In conclusion, we have computed $B_q\bar{B}_q$, $B_q\bar{B}_q^*+c.c.$, and $B_q^*\bar{B}_q^*$ $(q=d,s)$ production cross sections in the energy region from $\Upsilon(4S)$ to $\Upsilon(7S)$. As the above channels produce equal-sign dileptons at different rates, the partial production cross section is necessary to predict equal-sign-dilepton production rates. We predict that the most suitable beam energy to observe B-B mixing is at $\Upsilon(5S)$ or near 10.87 GeV. We have based our analysis on the values of x_s and x_d [Eq. (1)] obtained for $M_t\sim 35$ GeV. Once the t-quark mass is known, the measurement of the mixing effect will be a crucial test of the standard model.

Finally, we remind the reader that our analysis does not depend crucially on the dilepton decay channel [Eq. (3)]. It is also applicable for a decay channel in which B or B is identified by reconstruction.

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