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by

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AN UPDATE ON B^0-$\bar{B}^0$ MIXINGS

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ABSTRACT

An update on theoretical expectations and experimental searches of B^0-$\bar{B}^0$ mixing is presented. We determine bounds on the mixing probabilities in the B^0_d-$\bar{B}^0_d$ and B^0_s-$\bar{B}^0_s$ meson systems, $\chi(B_d), \chi(B_s)$. The upper bound $\chi(B_d) < 0.5$, obtained from the ARGUS data and the lower bound $\chi(B_s) > 0.57$ from the UA1 data are consistent with estimates in the Cabibbo-Kobayashi-Maskawa theory of flavour mixing.

Flavour changing neutral currents in the standard model /1/ are protected at the tree level by the generalized GIM mechanism /2/. In higher order weak interactions one could exchange, for example, a pair of W^+W^- bosons, which give rise to effective $\Delta F = 2$, $\Delta Q = 0$ interactions /3/ leading to K^0-$\bar{K}^0$, $D^0 - \bar{D}^0$, B^0-$\bar{B}^0$ etc. transitions. The quantities of phenomenological interest are the ratios $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where ΔM and $\Delta\Gamma$ are, respectively, the mass difference and the decay-width (equivalently life-time) difference between the two eigenstates of definite mass and life-time, and the quantity Γ is the average of the two decay widths $\Gamma = 1/2(\Gamma_H + \Gamma_L)$. The K^0-$\bar{K}^0$ sector is characterized by $x/y \simeq -1$ and $y \simeq 1$.

In the standard model with three families, one expects, in principle, five more examples of K^0-$\bar{K}^0$ type mixings /4/. However, quite generally, measurable mixing effects are expected only among mesons which are relatively long lived. Since the life-time of the charmed meson D^0 is not Cabibbo enhanced ($\tau_D \propto \cos^{-2}\theta_c$) but both $(\Delta M)_D$ and $(\Delta\Gamma)_D$ are Cabibbo suppressed, one expects x_D, $y_D \ll 1$. Likewise, for the neutral top mesons, x_T and y_T must be entirely negligible. This leaves then the other two bottom meson systems $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$, which have prima facie a chance to mix, since the average bottom hadron life-time is experimentally found to be relatively large, ($\tau_B \propto \sin^{-4}\theta$). In the rest of this talk I will concentrate on the bottom meson sector and review first the theoretical estimates and then the present experimental situation.

The diagrams contributing in leading order to ΔM and Γ for the bottom mesons are shown in fig. (1) /5/. Leading order QCD corrections to these diagrams have also been calculated /6/, as well as effects from the non-spectator diagrams on Γ_b are found to be small /7/. On the basis of this work one expects that QCD corrected spectator diagrams should provide a reasonable estimate for the bottom hadron inclusive widths and their semileptonic branching ratios. We shall, therefore, assume that $\tau(B_d) = \tau(B_s) = \tau(B_u^{\pm}) = \tau_b = (1.11 \pm 0.14) \times 10^{-12}$ sec. This equality should probably hold to within 10 %. The diagrams shown in fig. (1) lead to the following mass differences:

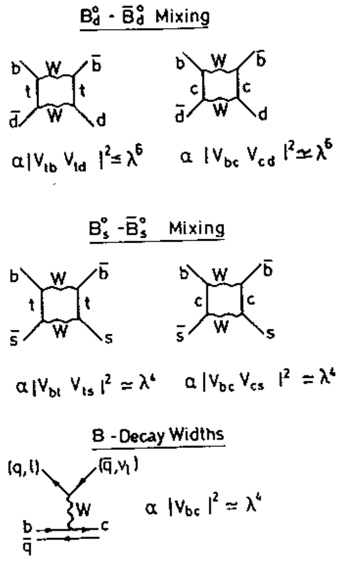

Fig. 1 Standard model contributions to $\Delta M(B_d^0)$, $\Delta M(B_s^0)$ and the resulting CKM angle dependence. The dominant contribution to Γ_b, common to all bottom hadron decays, is also shown, with its CKM angle dependence.

$$\Delta M(B_d^0) = \frac{G_F^2 m_W^2 B}{6\pi^2} f_{B_d}^2 m_{B_d} F_d(m_b, m_t, \lambda)$$

$$\Delta M(B_s^0) = \frac{G_F^2 m_W^2 B}{6\pi^2} f_{B_s}^2 m_{B_s} F_s(m_b, m_t, \lambda)$$

where f_{B_d} (f_{B_s}) is the B_d^0(B_s^0) pseudoscalar coupling constant analogous to f_π and B is the so called hadronic bag constant (B=1 in the vacuum saturation approximation). Recent theoretical calculation based on the QCD sum rules and SU(3) breaking effects give $Bf_{B_d}^2 = (115 \pm 15 \text{ MeV})^2$ with f_{B_s} approximately 25 % larger /8/. The box diagram functions F_d and F_s are dominated by the top quark contribution and a good estimate is provided by the expressions

$$F_d \simeq |V_{tb}^* V_{td}|^2 \frac{m_t^2}{m_W^2} \eta_2^B$$

$$F_s \simeq |V_{tb}^* V_{ts}|^2 \frac{m_t^2}{m_W^2} \eta_2^B$$

where η_2^B is a QCD correction factor, estimated /6/ to lie in the range $0.82 \leqslant \eta_2^B \leqslant 0.86$, and V_{ij} are the corresponding Cabibbo-Kobayashi-Maskawa matrix elements /9/. The expectations for the various KM matrix elements are /10/:

$$|V_{tb}| \simeq 1$$

$$|V_{ts}| \simeq |V_{bc}| \simeq \lambda^2$$

$$|V_{td}| \leqslant \lambda^3$$

where $\lambda \equiv \sin\theta_c \simeq 0.23$.

Thus, one expects $\mathcal{X}(B_s)$ to be Cabibbo allowed and $\mathcal{X}(B_d)$ to be Cabibbo suppressed as indicated in fig. (1). Theoretical estimates /4/ of $x(B_d)$ and $x(B_s)$ are shown in fig. (2) as functions of the top quark mass in the range 25 GeV $< m_t <$ 60 GeV, using $f_{B_d} = f_\pi$ = 130 MeV and $f_{B_s} = f_K$ = 164 MeV. In the indicated range of m_t, we expect $1.0 \leqslant x(B_s) \leqslant 4.0$ and $x(B_d) \leqslant 0.12$. The quantities $y(B_d^0)$ and $y(B_s^0)$ are both expected to be small /5-7/ (with $y(B_s^0)$ probably becoming as large as 0.05 /8/) and so we shall neglect them in subsequent calculations.

Since the lifetime of the bottom hadrons is very short to enable time dependent mixing effects, only time integrated effects of B^0-$\bar{B}^0$ mixing are measurable. A useful measure of M^0-$\bar{M}^0$ oscillations was introduced in refs. /11/, namely the ratio of "wrong-sign" to "right-sign" lepton in the semileptonic decays of M^0 and $\bar{M}^0$. Defining

$$r_q \equiv \frac{\Gamma(B_q^0 \to \ell^+ x)}{\Gamma(B_q^0 \to \ell^- x)} \qquad q = d,s$$

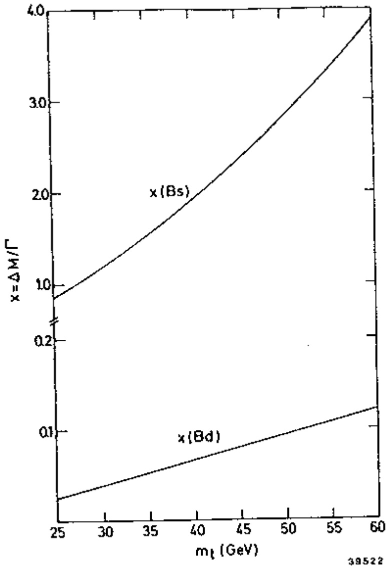

Fig. 2 Estimates of mixing probabilities $x(B_s) = \Delta M/\Gamma(B_s)$ and $x(B_d) = \Delta M/\Gamma(B_d)$ as a function of top quark mass (from ref. 4).

one can show that

$$\Upsilon_q = \frac{x_q^2 + y_q^2}{2 + x_q^2 - y_q^2} \simeq \frac{x_q^2}{2 + x_q^2} \xrightarrow[x_q \gg 1]{} 1$$

Based on the estimates of fig. (2) we expect

$$\Upsilon_d \lesssim 10^{-2}$$

$$\Upsilon_s \simeq 0.3 - 1$$

where we emphasize that the large difference in the values of Υ_d and Υ_s is essentially a reflection of the Cabibbo suppressed and allowed dependence of the box induced transitions.

In the analysis of experimental data it is often useful to define a quantity χ

$$\chi \equiv \frac{\Gamma(B \to \ell^+ X)}{\Gamma(B \to \ell^{\pm} X)}$$

The ratio χ, which is an average over the bottom mesons produced in a given experiment, is related to the specific ratios χ_q by the relation (χ_q is trivially related to Υ_q by the relation $\chi_q = \Upsilon_q/(1+\Upsilon_q)$)

$$\chi = \left[(BR)_d P_d \chi_d + (BR)_s P_s \chi_s\right]/\langle BR\rangle$$
$$\simeq P_d \chi_d + P_s \chi_s$$

where P_d and P_s are, respectively, the probability that a b quark produced in a high energy collision will end up in a $B_d^0 (= b\bar{d})$ or B_s^0 $(= b\bar{s})$ meson. The quantities $(BR)_d$, $(BR)_s$ and $\langle BR\rangle$ are the semileptonic branching ratios of the B_d, B_s mesons and the average over bottom hadrons, respectively. As remarked earlier one expects them to be almost equal.

A good measure of χ is the ratio of same-sign to opposite sign dileptons, $R(^{++}_{--}/+-)$, which is related to χ by the relation

$$R(^{++}_{--}/+-) = \frac{N(\ell^+\ell^+) + N(\ell^-\ell^-)}{N(\ell^+\ell^-)} = \frac{2\chi(1-\chi)}{\chi^2 + (1-\chi)^2}$$

It should be remarked that the relationship between $R(^{++}_{--}/+-)$ and χ given above holds for bottom meson production in the continuum, like for example in experiments at PEP, PETRA and hadron colliders. The relation between $R(^{++}_{--}/+-)$ and χ at a resonance, like for example Υ(4s), is more complicated due to the Bose-symmetry and angular momentum effects. The ratio $R(^{++}_{--}/+-)$ is enhanced in S-wave decays and suppressed in p-wave decays /12/. The expression for Υ_d in the analysis of ARGUS /13/ and CLEO data from Υ(4s) decays is

$$\Upsilon_d = \frac{N(B_d^0 B_d^0 + \bar{B}_d^0 \bar{B}_d^0)}{N(B_d^0 \bar{B}_d^0)} = \frac{\chi_d}{1-\chi_d}$$

For the sake of completeness, we also mention the method of the JADE collaboration in the search for B^0-$\bar{B}^0$ mixing /15/, which lies in the measurement of the electroweak forward-backward charge asymmetry, A_{FB}^b, involving bottom quarks. Denoting by $(A_{FB}^b)_0$ the asymmetry for the no-mixing case (i.e. $\chi = 0$) and by A_{FB}^b the actual experimental measurements, one can show that the ratio a_χ^b defined below satisfies the relationship,

$$a_\chi^b \equiv \frac{A_{FB}^b}{(A_{FB}^b)_0} = 1 - 2\chi$$

Now we turn to the experimental measurements. Experiments in e^+e^- annihilation (both on $\Upsilon(4s)$ and in continuum) carried out at PEP, PETRA, DORIS and CESR have yielded only upper limits for the measures $R(\overset{++}{--}/+-)$, Y_d and a^b_χ. They can be converted on limits for χ and χ_d; the 90 % C.L. limits are given below:

$\chi <$ 0.12 from $R(\overset{++}{--}/+-)$ MARK II /16/

$<$ 0.13 from a^b_χ JADE /15/

$\chi_d <$ 0.18 from Y_d CLEO /14/

$<$ 0.12 from Y_d ARGUS /13/

These upper limits should be contrasted with the expectations in the standard model. For the probability P_s estimated from K/π ratio, $P_s = 0.15 - 0.2$, one expects χ to lie in the range 0.075 - 0.1 for the MARK II and JADE measurements /16/. Though the PETRA/PEP measurements do not probe the standard model yet, they may not be too far away from seeing a positive effect in χ. The situation with the ARGUS and CLEO measurements is, however, quite different. The present DORIS/CESR limits on χ_d are at least one order of magnitude less sensitive than the expectations in the standard model. Before leaving the discussion of e^+e^- experiments, we remark that the ARGUS limit on χ_d gives an upper bound on the quantity $\mathcal{X}(B_d)$, namely $\mathcal{X}(B_d) < 0.5$, which, given m_t, can be translated into an upper bound on the CKM matrix element V_{td}. Using the present bound on m_t, $m_t > 23$ GeV, one gets $|V_{td}| < 0.05$, with the limit becoming $|V_{td}| < 0.024$ for $m_t > 60$ GeV.

The only positive indication of B^0-$\bar{B}^0$ mixing is reported by the UA1 collaboration /17/, through the measurements of the dimuon ratio $R(\overset{++}{--}/+-)$. With the acceptance cuts $p_T^{\mu_1,\mu_2} > 3$ Gev, $m_{\mu\mu} > 6$ GeV, $|\eta_\mu^{\text{Trigger}}| < 1.3$, $|\eta_\mu^2| < 2.0$, the UA1 collaboration has reported a sample of 257 $\mu^+\mu^-x$ and 142 $\mu^+\mu^+x + \mu^-\mu^-x$ events, giving /17/

$$R_{UA1}(\overset{++}{--}/+-) = 0.46 \pm 0.07 \pm 0.03$$

This is to be contrasted with the estimates of background /18/

$$R_{bgd.}(\overset{++}{--}/+-) = 0.24 \pm 0.03$$

This would then give /17,18/

$$\chi = 0.13 \pm 0.05$$

which is consistent with the standard model expectations and, within quoted errors, not in conflict with negative searches at PEP and PETRA. The measurement of χ can be converted to a lower bound on the quantity Y_s in the standard model. Setting $Y_d = 0$ and $P_s = 0.2$ one gets

$$Y_s > 0.14 \qquad (90\ \%\ \text{C.L.})$$

which gives in turn $x(B_s) > 0.57$. Again, a knowledge of $x(B_s)$ is essentially equivalent to a knowledge of the KM matrix element, given m_t. One gets $|V_{ts}| > 0.04$ for $m_t = 25$ GeV, this limit becomes $|V_{ts}| > 0.02$ for $m_t = 60$ GeV.

The non-zero measurement of Y_s constitutes the first experimental evidence that the matrix element V_{ts} is non-zero. Flavour correlations characteristic of B^0_s-$\bar{B}^0_s$ mixings /19/, however, have yet to be experimentally checked. This hopefully will be done at the forthcoming $\bar{p}p$ collider and e^+e^- experiments.

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