$D\bar{D}$ and $B\bar{B}$ mixing

Paolo Checchia
Istituto Nazionale di Fisica Nucleare sezione di Padova, Padova, Italy

Abstract

The results on D^0 and B^0 mixing are reviewed. The status of searches for D^0 mixing is given and the role of the interference with doubly-Cabibbo-suppressed decays is discussed. Both integrated and time dependent measurements on B_d^0 decays are presented: a very good precision on Δm_d determination is reached. Limits on Δm_s are given.

1 Introduction

The mixing phenomenon, introduced to describe the K^0 system[1], has been observed in the B^0 system since 1987 [1]. The standard way to describe a change of the flavour quantum number by two units is via the second order weak interaction box diagrams as in Fig. 1. The box diagram contributions can be computed, for the B^0, with a $10 \div 40\%$ precision and it is then possible to deduce from experimental quantities informations on the Standard Model parameters. The expected mixing in the D^0 system is strongly suppressed with respect to the B^0 one. In the D^0 system, flavour-violating transitions produced by long-distance processes to common intermediate states (e.g. $\pi^+\pi^-$ or K^+K^-) are dominant by one or two orders of magnitude [2]. The long-distance contributions cannot be precisely computed but they are negligible for B^0 mixing.

The CP eigenstates $|B_1\rangle$ and $|B_2\rangle$ can be obtained from the flavour eigenstates $|B^0\rangle, |\bar{B}^0\rangle$ via: $|B_1\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle + |\bar{B}^0\rangle)$, $|B_2\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle - |\bar{B}^0\rangle)$. Assuming CP is conserved, they correspond to the mass eigenstates. The time evolution for flavour states is given by the Schrödinger equation and then, having a B_q^0 $(q = d, s)$ meson at $t = 0$, the probability to observe a $B_q^0[\bar{B}_q{}^0]$ decaying at the time t is (neglecting CP violation and assuming the Standard Model prediction $\Delta\Gamma_q \ll \Delta m$):

$$\mathcal{P}(B_q^0 \to B_q^0[\bar{B}_q{}^0]) = \Gamma_q e^{-\Gamma_q t} \cos^2[\sin^2](\frac{\Delta m_q t}{2}) \qquad (1)$$

[1] Unless explicitely stated, charged conjugate states are always implied

where $\Gamma_q = \frac{\Gamma_q^1 + \Gamma_q^2}{2}$, $\Delta\Gamma_q = \Gamma_q^1 - \Gamma_q^2$ and $\Delta m_q = m_q^1 - m_q^2$. The mass difference is thus related to the measurable frequency of the oscillation. Defining the quantity $x_q = \frac{\Delta m_q}{\Gamma_q}$, the integrated probability for mixing is:

$$\chi_q = \frac{x_q^2}{2(1 + x_q^2)}. \tag{2}$$

In the Standard Model the CKM matrix describes the coupling between up- and down-type quarks. Imposing unitarity conditions it can be expressed in terms of four independent parameters and, following the Wolfenstein parametrization [3], it can be written as:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

where $\lambda = \sin\theta_c = 0.2205 \pm 0.0018$ [4] and A=0.80 $\pm$ 0.12 [5] are measured while ρ and η (related to CP violation) are little constrained. The unitarity condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ corresponds to a triangle on the (ρ, η) plane as shown in Fig.2. The present uncertainties on the sides and on the angles of the triangle are discussed in detail in ref.[5]. Since $|V_{cb}| \sim |V_{ts}|$ the side **AB** can be reexpressed in term of the ratio $\left|\frac{V_{td}}{\lambda V_{ts}}\right|$.

The value of Δm_q can be compared to the Standard Model prediction which is dominated by the top quark box diagrams:

$$\Delta m_q = \frac{G_F^2}{6\pi^2} M_{B_q}\eta_{B_q}B_{B_q}f_{B_q}^2 m_t^2 F(\frac{m_t^2}{M_W^2})|V_{tq}V_{tb}^*|^2 \tag{3}$$

where η_{B_q} , the correction due to strong interaction and F , which parametrizes the dependence on the top mass, are known with sufficient precision while the terms B_{B_q} and $f_{B_q}^2$ are poorly known. Various calculations from lattice and QCD sum rules can be summarized to give $f_{B_d} = (180 \pm 50)$ MeV and $B_{B_d} = 1.0 \pm 0.2$. The theoretical uncertainty on these two terms gives the largest contribution ($\sim 30\%$) to the error on the $|V_{td}|$ (and $\left|\frac{V_{td}}{V_{cb}}\right|$) determination from a precise measurement of Δm_d. On the other hand, if both Δm_d and Δm_s are measured, on the ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{B_s}\eta_{B_s}B_{B_s}f_{B_s}^2}{M_{B_d}\eta_{B_d}B_{B_d}f_{B_d}^2}\left|\frac{V_{ts}}{V_{td}}\right|^2 \tag{4}$$

the factor $\xi_s = \frac{f_{B_s}\sqrt{B_{B_s}}}{f_{B_d}\sqrt{B_{B_d}}}$ is known with a better precision ($\xi_s = 1.16 \pm 0.10$) and consequently the error on the $\left|\frac{V_{td}}{V_{ts}}\right|$ ratio due to the theory can be reduced to about 10%. This shows the importance of the measurement of Δm_s which would imply a quite precise knowledge of the side **AB** of the triangle of Fig. 2.

2 D^0 mixing

On the D^0 system the box diagram contribution to the mixing is strongly suppressed ($x_D = \frac{\Delta m_D}{\Gamma_D} \sim 2{\cdot}10^{-6}$), the long-distance contribution dominates and the expectation is to have an integrated mixing probability well below 10^{-4}. Therefore a larger D^0 mixing would be an evidence for new physics. A typical signature for D^0 mixing is $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$ or the ratio $r_{mix} = \frac{\Gamma(D^0 \rightarrow \bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f)}$ where $\bar{f}$ (f) corresponds to the wrong (right) sign of the D^0 decay products : $K^+\pi^-$ ($K^-\pi^+$), $K^+\pi^-\pi^+\pi^-$ etc.. However the wrong sign final states can be obtained via Doubly Cabibbo Suppressed decays (DCS) which are expected to occur at a rate $r_{DCS} \sim \mathcal{O}(\tan^4\theta_c) \sim 3 \cdot 10^{-3}$. The total wrong-to-right-sign ratio r_{ws}, neglecting terms proportional to $\Delta\Gamma$, can be expressed as $r_{ws} \sim r_{mix} + r_{DCS} + r_{int} \sim x_D^2/2 + |\mathcal{E}|^2 + x_D Im(\mathcal{E})$ where the third term is due to the interference between mixing and DCS contributions. The three terms have a different time dependence and, for very small values of x_D, the decay rate of wrong sign events is : $ws(t) \sim e^{-t/\tau}(|\mathcal{E}|^2 + \frac{x_D^2}{4}\frac{t^2}{\tau^2} + Im(\mathcal{E})x_D\frac{t}{\tau})$. Recently it has been claimed [6] that the interference term cannot be neglected as it was in the past. Neglecting the interference term from the fit to the data would imply an overestimate of the experimental sensitivity.

An evidence of $D^0 \rightarrow K^+\pi^-$ decay, with the D^0 state tagged by the $D^{*+} \rightarrow D^0\pi^+$ decay has been observed by CLEO [7]. A clear signal on the $D^* - D^0$ mass difference for events having a peak on the $K^+\pi^-$ invariant mass is seen (Fig. 3). The measured r_{ws} is $r_{ws} = (0.77 \pm 0.25$ (stat) ± 0.25 (syst) $)\%$ but time measurement to separate mixing, DCS and interference contributions is not available. This is not the case for a similar analysis done, with the addition of the $K\pi\pi\pi$ channel, by the Fermilab experiment E791, equipped with a multilayer vertex detector. Clear peaks are present in the region corresponding to the $D^* - D^0$ difference of mass and invariant mass of right sign D^0 decays, while there is not signal in the wrong sign plots (Fig. 4). From a fit to the time dependent data distribution, the three parameters r_{mix}, r_{DCS} and r_{int} are obtained with preliminary values all compatible with zero [8]. Given the preliminary state of the analysis, upper limits are not yet quoted. E791 gives also a value for the total wrong sign rate : $r_{ws} = (0.90^{+.83}_{-.71})\%$. The present published limit on r_{mix} ($r_{mix} < 0.37\%$ at 90% C. L.), obtained by the experiment E691 [9], neglects the interference term, so a more correct limit is $r_{mix} < 0.7\%$ at 90% C. L. including the interference [9] [10].

3 Experimental methods for b mixing measurement

The measurements of the b mixing can be either time-integrated or time-dependent. At LEP it is possible to divide the event in two hemispheres assuming each contains a $b(\bar{b})$ quark and in both it is performed a tag of the production (or decay) charge of the quark. Assuming the two charge determinations as independent, the event is classified as mixed if their product is positive, unmixed in the opposite case.

The determination of the quark charge relies on the following methods: 1) charge of the decay charm meson, 2) charge of a high p_t lepton, 3) charge of the jet (hemisphere), 4) charge of identified kaons. The purity on the charge measurement is a crucial parameter on the experimental sensitivity for b mixing. In fact the wrong assignment rate ϵ produces a reduction factor $(1-2\epsilon)$ on the experimental sensitivity.

The semiexclusive decays of a B meson on a charged charm meson as $B_d^0 \rightarrow D^{*-} + X$, give a good signature of the b quark charge at the decay time. These channels enrich the content of the required $B-$hadron in the event sample (B_d^0 or B_s^0 for final states with D^* or D_s respectively) but they suffer for a limited statistics and a contamination from the charmed meson production from $Z^0 \rightarrow c\bar{c}$ events and from the combinatorial background.

An alternative tag is provided by the lepton charge q_l in semileptonic $B-$hadron decays. The contamination due to the opposite-charged leptons coming from $b \rightarrow c \rightarrow l$ cascade decays can be minimized by requiring leptons with high momentum and high transverse momentum (p_t) with respect to the jet direction. Typical purities of the order of 90% can be achieved.

A largely used tag method giving an acceptable purity of $\sim 70\%$ and a large statistical sample is a momentum (or rapidity) weighted charge technique, the so called jet (or hemisphere) charge. The jet (hemisphere) charge is defined as $Q_{jet} = \frac{\sum_{i=1}^{n} q_i p_i^k}{\sum_{i=1}^{n} p_i^k}$ (or with similar definitions) where q_i and p_i are, respectively, the charge and the momentum of the ith track of the jet (hemisphere) and k is chosen in the range between 0 and 1. This estimator is used in general to tag the charge in the hemisphere opposite to the one (time hemisphere) having the measured proper time and the charge determined with one of the previous methods. However a combination of the jet charge in the opposite and in the time hemisphere can also be used.

In the time-dependent measurement the time dependence of the number of decays

(N^m) in events classified as mixed and of the number of decays (N^u) in events classified as unmixed is studied. The proper time $t = l \cdot \frac{m_B}{cp_B}$ is obtained by the independent measurements of the decay length l and of the boost $\frac{m_B}{cp_B}$. It is therefore necessary to reconstruct, by means of silicon microvertex detectors, the secondary vertex corresponding to the $B-$hadron decay and to estimate its momentum from the decay products. The vertex reconstruction is easy in the semiexclusive channels, where the tracks from the charm final states are identified, while, in the semileptonic decays, vertex algorithms have to be introduced to find the other B decay tracks. Since $\frac{\sigma_t}{\tau} \sim \sqrt{(\frac{\sigma_l}{<l>})^2 + (\frac{\sigma_p t}{p\tau})^2}$ and, at LEP, the momentum spectrum for $B-$hadrons is quite peaked around its average value, the time resolution is dominated by the decay-length resolution at $t \sim 0$ and grows with the proper time. The typical narrow component for σ_t at $t \sim 0$ is about $.2 \div .25$ ps. The effect of the resolution is much more important in the case of high frequency oscillation since it introduces a damping factor $e^{\frac{(\sigma_t \Delta m)^2}{2}}$ to the oscillation amplitude. This effect is negligible for B_d^0 but critical for B_s^0 mass differences above $5 \div 7\ ps^{-1}$. The second term on the resolution equation, with a momentum resolution of about $10 \div 20\%$, typical of LEP experiments, dominates at long proper time and thus the relevant time range to study the B_s^0 oscillations is limited to a few lifetimes.

4 Time integrated b mixing

The time-integrated probability for mixing is given by eq. 2. This measurement can be done by requiring two semileptonic decays in the event and considering the ratio $R = \frac{N^m}{N^m + N^u}$. At the $\Upsilon(4s)$ the $B_d^0 \bar{B}_d^0$ pairs are produced in a coherent state and then $\chi_d = (1 + \lambda)R$ where λ takes into account the unmixed contribution of B^+B^- pairs. Since λ depends on the charged to neutral B lifetime ratio, from the latest measurements [11] one gets: $\lambda = 1.16 \pm .17$. Other measurements are weakly dependent on λ and the results at $\Upsilon(4s)$ are summarized in Fig. 5 giving an average $\chi_d = 0.169 \pm 0.022$.

At LEP the $B\bar{B}$ production is incoherent and both the B_d^0 and B_s^0 states are produced. The ratio R therefore gives an average measurement of the two mixing probabilities weighted by the production fractions: $R \sim 2\bar{\chi}(1 - \bar{\chi})$ with $\bar{\chi} = f_d \chi_d + f_s \chi_s$. The most precise result for $\bar{\chi}$ is given by the LEP Electroweak working group after a full averaging procedure applied to the measured quantities on the heavy quark sector [16]: $\bar{\chi} = 0.116 \pm 0.006$. Including results from $p\bar{p}$ colliders [17] and assuming the same proportion of B_d^0 and B_s^0, the world average is $\bar{\chi} = 0.118 \pm 0.006$.

5 Time dependent B_d^0 mixing

B_d^0 oscillations can be measured by the time dependence of the semiexclusive decays $\bar{B}_d^0 \to D^{*+}(l^-)X$, with $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+(\pi^0)$, with the lepton or the jet charge tag in the opposite hemisphere. ALEPH, DELPHI and OPAL make similar analyses, all dominated by the statistics.

A second possibility to measure Δm_d is to study the lepton tagged events in the time hemisphere and to tag the charge on the opposite hemisphere again with lepton or jet charge. DELPHI profits also from identified kaons to tag on both the time and the opposite hemisphere. The mixed fraction R obtained by OPAL [24] in the 91-93 dilepton events, shown in Fig. 6, presents a clear time oscillation. The same fraction R for lepton-jet events as obtained by DELPHI including also 94 data is shown in Fig. 7. ALEPH measures Δm_d on lepton-jet events [22] looking at the time dependence of the average product of the lepton charge times the jet charge (Fig. 8). In the lepton tagged decays there is a contribution from the B_s^0 as well and, to extract the Δm_d measurement, very large Δm_s, corresponding to maximal B_s^0 mixing, is assumed. The systematic error on the lepton tagged Δm_d measurements is comparable to the statistical one.

A summary of all the Δm_d measurements is given in Fig. 9. The systematic errors of the different measurements are partially correlated but it is rather arbitrary to extract the common part from all the contributions. Therefore, given the preliminary state of most of the results, here it has been decided to average the LEP results assuming independent systematic errors, with the obvious warning that the obtained result has a slightly underestimated total error. The last measurement done by CDF [26] and the result from the time integrated measurement at the $\Upsilon(4s)$, assuming for the B_d^0 lifetime $\tau_{B_d^0} = 1.58 \pm 0.06\ ps$ [11], are included. The world average is then: $\Delta m_d = (0.472 \pm 0.022) ps^{-1}$.

6 Estimate of the B_s^0 fraction

Given the very precise time dependent measurement of Δm_d, the B_d^0 lifetime and the $\Upsilon(4s)$ measurement, the best value for the integrated B_d^0 mixing is $\chi_d = 0.178 \pm 0.012$. From $\bar{\chi} = f_d\chi_d + f_s\chi_s$ and assuming the same production rates f_u and f_d for B^+ and B_d^0 states, so that $2f_d + f_s + f_{\Lambda_B} = 1$, one gets:

$$f_s = \frac{2\bar{\chi} - \chi_d(1 - f_{\Lambda_B})}{2\chi_s - \chi_d}$$

where f_{Λ_B} is the fraction of $B-$baryons assumed to be $(10 \pm 4)\%$. If the B_s^0 has a maximal mixing (see next section), χ_s is about .5 and then it is possible to extract

$f_s = (9.2 \pm .9(f_{\Lambda_B}) \pm 1.5(\bar{\chi}) \pm 1.2(\chi_d)\ )\%$ where the different contributions to the error are specified. Combining the errors in quadrature $f_s = (9.2 \pm 2.1)\%$ and this is the most precise estimate of the B_s^0 fraction in b events. Since the largest contribution to the error comes from the $\bar{\chi}$ measurement, this result can be improved in the future.

7 B_s^0 mixing

There are two factors making the Δm_s measurement much harder than the Δm_d one: the B_s^0 production rate, which is about one forth of B_d^0 one; the oscillation frequency which is expected to be higher and then more difficult to detect, given the damping factor due to the time resolution.

As in the case of B_d^0, semiexclusive or inclusive tagging on the time hemisphere is used. DELPHI has studied the former by looking at the channel $B_s^0 \to D_s^- l^+ X$ with D_s reconstructed from the $KK\pi$ invariant mass. With a limited statistics (only 91-93 data sample), a preliminary lower limit is given: $\Delta m_s > 1.5\ ps^{-1}$ at the 95% C.L. [27].

The inclusive methods are based on l-l (ALEPH,OPAL) and l-jet (ALEPH,DELPHI) analyses, with the inclusion of a l-jet analysis (ALEPH) on which the B_s^0 mixing is tagged by using also the sign of the fragmentation kaons on the time hemisphere [28]. On the 91-93 l-l sample OPAL [24] performs a maximum likelihood fit to Δm_s after fixing Δm_d to the average LEP value excluding dilepton results. The difference in log-likelihood from the maximum likelihood point (ΔL) is shown in Fig. 10 without systematic errors (dashed curve) and including the effect of systematics (solid curve). All the values of Δm_s giving $\Delta L > 1.92$ are excluded at 95% confidence level. The inclusion of the systematics reduces the limit from 2.3 to 2.2 ps^{-1}. A similar analysis is performed by ALEPH on dilepton events [21]. In this case, however, the inclusion of systematic effects is done by means of a fast Monte Carlo producing several samples having a statistics equivalent to the data at different input values of Δm_s. The 95% level contour is determined by smearing the parameters of the fitting functions and the limit is set on the point of intersection of the contour with the data ΔL curve. This method gives $\Delta m_s > 3.9\ ps^{-1}$ (95% C.L.). The technique to include the systematic error on the 95% C.L. contour, has been used by ALEPH in the measurement obtained with the lepton and the fragmentation kaon [28] . From 91-94 data sample this measurement gives $\Delta m_s > 3.2\ ps^{-1}$ (95% C.L.).

Two other analyses based on l-jet events provide limits on Δm_s . DELPHI, from the whole 91-94 data sample used to measure Δm_d, obtaines a ΔL curve as a function of Δm_s as shown in Fig. 11 [25]. To set a limit on Δm_s including the systematic effects, ΔL is recomputed, for different value of Δm_s, changing the input parameters according to the their errors (in Fig. 11 the effect of changing f_s is shown). The Confidence Level, corresponding to a given value of ΔL, is computed with a fast Monte Carlo. The limit is $\Delta m_s > 3\ ps^{-1}$ at 94.1% C.L.. The second analysis is done by ALEPH which uses a modified jet-charge technique, weighting the track charge with the rapidity and using both the hemispheres [29]. The corresponding ΔL for the 91-94 data set, as function of Δm_s, is shown in Fig. 12 a). The 95% confidence level contour is determined with a fast Monte Carlo including all the systematic contributions but the f_s one. The 95% confidence level Δm_s lower limit as function of f_s as shown in Fig. 12 b). It is suggested $f_s = 12\%$ for which $\Delta m_s > 6.1\ ps^{-1}$. The limit at $f_s = 10\%$ is $\Delta m_s > 5.6\ ps^{-1}$.

In conclusion, many new analyses on the B_s^0 oscillation were performed during the last year [30]. Unfortunately the techniques to set the limit and to treat the systematics are different among experiments making it impossible to deduce a global limit from all the results. From $\Delta m_s > 6\ ps^{-1}$ and $\Delta m_d = 0.472 \pm 0.022\ ps^{-1}$, $\frac{\Delta m_s}{\Delta m_d} > 12.1$ and then, from eq. 4, $\left|\frac{V_{td}}{V_{ts}}\right|^2 > 7.56$.

8 Conclusions

On the charm sector there is evidence of the wrong sign decay $D^0 \to K^+\pi^-$ and the existing limit on the mixing contribution is $r_{mix} < .7\%$ at 90% confidence level, still not very stringent.

From time-integrated and time-dependent B_d^0 mixing measurements, a very precise value of Δm_d is obtained: $\Delta m_d = 0.472 \pm 0.022\ ps^{-1}$ leaving the contribution to the error on the $|V_{td}|$ evaluation totally dominated by the theory uncertitudes. Using the B_d^0 mixing χ_d and the global mixing $\bar{\chi}$, the B_s^0 meson production fraction is estimated: $f_s = (9.2 \pm 2.1)\%$.

With a subset of the LEP 94 data analyzed, a lower limit on the B_s^0 mixing is given: $\Delta m_s > 6\ ps^{-1}$ at 95% confidence level. A common procedure to combine the different results is envisaged in particular to include new analyses becoming competitive with the inclusion of new data.

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