$B^0\bar{B}^0$ OSCILLATIONS AT LEP

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Abstract

Recently updated measurements of the $B^0\bar{B}^0$ mixing parameter at the LEP storage ring are reported. The combined result from ALEPH, DELPHI, L3 and OPAL dilepton analyses is $\bar{\chi} = 0.119 \pm 0.012$. The first observation of the time dependence of the $B^0\bar{B}^0$ oscillations is presented. Clear evidence for the time-dependent nature of the $B_d^0\bar{B}_d^0$ oscillation has been found by the ALEPH collaboration, using the vertex structure and charge correlation in D^*-lepton and dilepton events. The frequency extracted from a fit to the D^*-lepton distribution corresponds to a mass difference between the B_d^0 states,

$$\Delta m = [3.44\ ^{+0.65}_{-0.70}(\mathrm{stat})\ ^{+0.26}_{-0.20}(\mathrm{syst})] \cdot 10^{-4} eV\ .$$

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1 Phenomenology of $B^0\bar{B}^0$ mixing

In analogy to the neutral kaon system, the beauty eigenstates B^0 and $\bar{B}^0$ are not mass eigenstates, but linear combinations of the CP eigenstates B_1^0 and B_2^0, with mass eigenvalues $m \pm \Delta m/2$. The wave function of an initially pure B^0 state therefore has two components with different frequencies, which gives rise to oscillating probabilities to observe a B^0 or a $\bar{B}^0$ meson at decay time:

$$\begin{aligned} B^0(t) &= e^{-t/\tau} \cdot (1 + \cos\Delta m t)/2 \,, \\ \bar{B}^0(t) &= e^{-t/\tau} \cdot (1 - \cos\Delta m t)/2 \end{aligned} \tag{1}$$

(in units $\hbar = c = 1$). The $B^0 \leftrightarrow \bar{B}^0$ transition is understood in the Standard Model in terms of the so-called box diagrams involving virtual top quark exchange. Evaluation of the diagrams gives the mass difference Δm that depends on the mass of the top and its weak couplings to the light quarks.

The time-integrated probability for an initially pure B^0 state to decay as a $\bar{B}^0$ is

$$\chi \equiv \text{Prob}(B^0 \to \bar{B}^0) = \frac{1}{2}\frac{x^2}{(1+x^2)} \,, \quad x = \Delta m \cdot \tau \,. \tag{2}$$

(τ is the B lifetime.) This has been measured for B_d^0 mesons by the ARGUS and CLEO experiments at the $\Upsilon(4S)$ energy [1, 2]. At LEP energies, b quarks are produced in decays of the Z resonance, and one measures [3, 4, 5, 6] the average mixing parameter

$$\bar{\chi} \equiv \text{Prob}(b \to B_{d,s}^0 \to \bar{B}_{d,s}^0) = f_d\chi_d + f_s\chi_s \,, \tag{3}$$

where f_d and f_s are the B_d^0 and B_s^0 production fractions in $Z \to b\bar{b}$ events. The time-dependent nature of $B^0\bar{B}^0$ oscillations has not previously been demonstrated experimentally.

2 Time-integrated Measurements of the Mixing Parameter $\bar{\chi}$

In $Z \to b\bar{b}$ events, in which both b hadrons decay semileptonically, the leptons carry charges of opposite sign, unless mixing occurs. The proportion of events containing two leptons (electrons or muons) with like charge sign in opposite jets thus provides a measure of the $B^0\bar{B}^0$ oscillation strength. This is diluted mainly by cascade decays $b \to c \to \ell$ where the leptons originate from secondary charm hadrons and carry the opposite charge sign to the primary b decay. In order to discriminate the signal against this process, one exploits the harder momentum and transverse momentum (p and $p_\perp$) spectrum of primary leptons with respect to secondary leptons. Other background sources, $c\bar{c}$ events and hadron misidentification, also populate the low p, $p_\perp$ region.

The DELPHI collaboration forms a combined variable $p_{\text{comb}} = \sqrt{(p_\perp^2 + p^2/70)}$. They extract the mixing parameter from a two-dimensional Maximum Likelihood fit to the observed fraction of like-sign dilepton events as a function of $p_{\text{comb}}^{(1)}$ and $p_{\text{comb}}^{(2)}$, where the superscripts refer to the two leptons. The underlying distributions used in the fit are obtained from a Monte Carlo simulation and have been adjusted to the measured single lepton spectra. Data taken in 1991 and 1992, amounting to 940000 hadronic Z decays, are included in the analysis, giving the preliminary value

$$\bar{\chi} = 0.131 \pm 0.015 \pm 0.017 \,, \tag{4}$$

where the first error is statistical and the second systematic. The systematic error is predominantly due to uncertainties in the branching ratios $B(b \to \ell)$, $B(b \to c \to \ell)$, $B(c \to \ell)$.

The L3 collaboration has also used data taken in 1992 to update their mixing measurement. Their sample now corresponds to an integrated luminosity of $38.7 pb^{-1}$. A fit to the like-sign fraction is performed in $p^{(1)}$, $p_\perp^{(1)}$, $p^{(2)}$, $p_\perp^{(2)}$ space, as described in [5]. The new preliminary result is

$$\bar{\chi} = 0.118 \pm 0.012 \pm 0.010 \,. \tag{5}$$

The systematic uncertainty of this method arises mainly from Monte Carlo statistics, since the simulated event distributions must be binned in four dimensions. Additional contributions to the error quoted here are expected to result from a study of model dependence that is currently in progress.

The ALEPH approach consists in simultaneously measuring various parameters associated to heavy quark production and decay in a global fit to single lepton and dilepton event distributions. This allows correlations between the parameters to be properly taken into account. The source of information determining each of the parameters can, however, be identified. Single lepton p, $p_\perp$ distributions yield the product $\Gamma(Z \to b\bar{b}) \cdot B(b \to \ell)$ and the fragmentation parameter $\langle x_b \rangle$ (from the high $p_\perp$ region) as well as $\Gamma(Z \to c\bar{c}) \cdot B(c \to \ell)$ and $\langle x_c \rangle$.

Dilepton events are analyzed in terms of $p_\perp^{min} = \min(p_\perp^{(1)}, p_\perp^{(2)})$ and $p_\otimes = p_\perp^{(1)} p_\parallel^{(2)} + p_\perp^{(2)} p_\parallel^{(1)}$. The sample is split into events with both leptons in either the same or the opposite hemisphere. The same side events are dominated by the cascade process and give $B(b \to c \to \ell)$. The opposite side events allow the branching ratio $B(b \to \ell)$ to be extracted. Finally, the mixing parameter is determined from the like-sign fraction in opposite side events with $p_\perp^{min} > 1\,GeV/c$. From data taken in 1990 and 1991,

$$\bar{\chi} = 0.114 \pm 0.014 \pm 0.008 \tag{6}$$

is obtained. Here, the uncertainties arising from the errors of simultaneously measured parameters like, e.g. $B(b \to \ell)$ are included in the statistical error. The systematic error mainly reflects the model dependence of the result. This was estimated by varying the shapes of the lepton momentum spectra in the Monte Carlo simulation according to the models of Altarelli *et al.* [7] and of Isgur *et al.* [8]. ALEPH cross-check their result by a control analysis in which single parameters are measured separately by counting methods.

The OPAL collaboration quotes the result already presented in [9]:

$$\bar{\chi} = 0.125 \pm 0.017 \pm 0.015\,, \tag{7}$$

from a one-dimensional fit to a combined variable.

The four measurements agree well with each other. The weighted LEP average is

$$\bar{\chi} = 0.119 \pm 0.012\,, \tag{8}$$

where common systematic errors are accounted for. A model dependence of ±0.007 (as results from the ALEPH study) is attributed to the average as well.

ALEPH and DELPHI have also performed measurements of $B^0\bar{B}^0$ mixing using a jet-charge method [10]. These are subject to larger systematic uncertainties and are not included here.

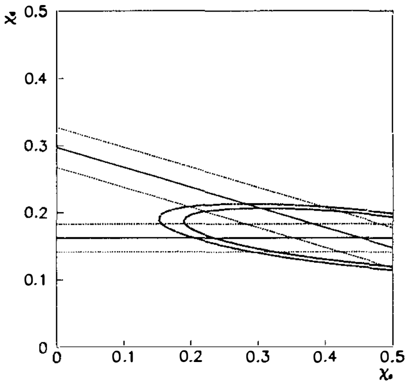

Figure 1: Combination of the LEP measurements of $\bar{\chi}$ with the χ_d measurements of ARGUS and CLEO (horizontal band). Dotted lines show $\pm 1\sigma$ errors, the solid (dashed) ellipse represents the combined 90 (95) % C.L. contour.

Constraints on the B_s^0 mixing parameter χ_s are obtained from the combination of the LEP measurements with the χ_d measurements using $\Upsilon(4S)$ data, if further assumptions are made. The production fractions $f_d = 0.4$ and $f_s = 0.12$ are consistent with a strange quark suppression factor of 0.3 inferred from measurements of the relative kaon and pion rates at LEP energies [11]. The semileptonic branching ratios of the individual B meson species are assumed to be equal in the definition of $\bar{\chi}$ (Eq. 3). The weighted average of the ARGUS result [1] and the updated CLEO dilepton measurement [12] is

$$\chi_d = 0.162 \pm 0.021\,, \tag{9}$$

if equal production rates of B^+B^- and $B^0\bar{B}^0$ pairs are assumed, and if the same assumption on semileptonic decays as above is made. (The additional systematic error on χ_d arising from uncertainties in these two assumptions is ± 0.021, but is not included here.) The χ and χ_d measurements are represented in the χ_d, χ_s plane in Fig. 1, which shows the combined 90 (95)% confidence level contours as a solid (dashed) ellipse. This corresponds to

$$\chi_s = 0.45 \pm 0.12 \text{ or } \chi_s > 0.25 \text{ at } 90\%\text{C.L.} \tag{10}$$

For a different choice of production fractions, $f_d = 0.375$ and $f_s = 0.15$, the 90% C.L. limit is $\chi_s > 0.23$.

In the Standard Model one expects χ_s close to 0.5; the unitarity of the Kobayashi-Maskawa matrix requires $x_s > 8$ approximately [13]. For such large values of $x = \Delta m\,\tau$ the time-integrated mixing parameter χ has almost no sensitivity to the oscillation frequency. Better constraints on x_s can only be obtained by methods directly referring to the time dependence of mixing.

3 Observation of the Time Dependence of $B^0\bar{B}^0$ Mixing

The first method used by ALEPH selects D^*-lepton events. Since D^{*-} mesons originate predominantly from B_d^0 decays, the method is essentially sensitive to $B_d^0\bar{B}_d^0$ oscillations. The lepton on the opposite side of the event tags the B at $t = 0$, the charge of the D^* meson serves as tag at decay time. Here, mixed events result in unlike-sign pairs. One studies the charge correlation

$$C_Q = \frac{N^{\text{like}} - N^{\text{unlike}}}{N^{\text{like}} + N^{\text{unlike}}} = \frac{N^{\text{unmixed}} - N^{\text{mixed}}}{N^{\text{unmixed}} + N^{\text{mixed}}}\,. \tag{11}$$

With perfect purity and resolution, $C_Q = \cos \Delta m t$ would hold. In practice, the D^* decay vertex (= the B vertex) cannot be well reconstructed, but one uses the daughter D^0 vertex instead. The B momentum is not measured, so C_Q as function of decay length rather than time is convoluted with the B fragmentation spectrum. Lepton mistags due to cascade decays or mixing reduce the amplitude of the oscillation. $c\bar{c}$ background gives unlike-sign correlations and distorts the distribution at short decay lengths.

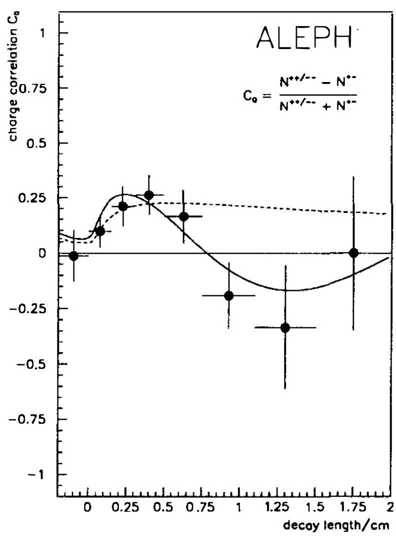

Figure 2: D^*-lepton charge correlation C_Q as function of decay length, measured by ALEPH. The solid line shows the result of a fit allowing for oscillations, the dashed line shows a non time dependent model.

In the data taken in 1990-92, reconstructing the decay modes $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$, 664 candidate events are selected, with a signal to combinatorial background ratio of roughly 1 : 1. The measured charge correlation function is presented in Fig. 2.

Also displayed (as a solid line) is the result of an unbinned Maximum Likelihood fit to the like-sign and unlike-sign event distributions. The extracted oscillation frequency corresponds to a mass difference

$$\Delta m = [3.44\ ^{+0.65}_{-0.70}(\text{stat})\ ^{+0.26}_{-0.20}(\text{syst})] \cdot 10^{-4} eV\ . \tag{12}$$

Additional free parameters in the fit were the $B^+ \rightarrow D^*$ and $c\bar{c}$ background fraction and the lepton mistag rate. The fitted values agree with expectation, and their uncertainties are accounted for in the statistical error. Shown as a dashed line is a fit with the hypothesis of time-independent mixing. The likelihood difference corresponds to disfavoring this hypothesis by 3.2 standard deviations. The systematic error receives contributions from uncertainties in the B^+ and combinatorial background charge correlation, the B^0_d, B^+ and D^0 lifetimes, the resolution function, the b fragmentation and the average D^0 momentum. In order to compare the fundamental quantity Δm to time-integrated measurements, one has to multiply with the exclusive B^0_d lifetime $\tau(B^0_d) = 1.44 \pm 0.15\,ps$ (combined ALEPH, DELPHI and OPAL measurements [14]), and one obtains, including the extra error,

$$x_d = 0.75\ ^{+0.15}_{-0.14}(\text{stat})\ ^{+0.08}_{-0.05}(\text{syst})\ , \tag{13}$$

consistent with Eq. 9.

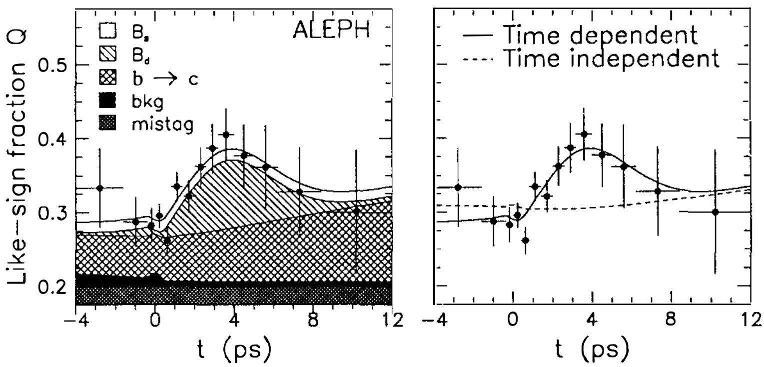

Figure 3 : Like-sign fraction of dilepton events, as a function of decay time, measured by ALEPH. The solid line is a fit with x_d and $\tau(B^0_d)$ as free parameters. Left, the contributions to the observed distribution are displayed. Right, the fit of the rejected time-independent model is shown as dashed line.

The second method uses opposite-side dilepton events. It is therefore in principle also sensitive to B^0_s oscillations. ALEPH calculates the B decay distance in such events by means of an inclusive vertexing technique. First, the primary vertex is found, also using the beamspot that is determined from the charged tracks of groups of 100 events. As only few charged particles, apart from the lepton, are expected from the B vertex, the charm decay vertex is reconstructed next. Using the charged tracks in each hemisphere (excluding the lepton), a secondary vertex is searched for by comparing the χ^2 for various vertex hypotheses on a suitable grid. The inferred charm track is finally vertexed with the lepton to give the B decay point. In order to convert the decay distance d into proper time t,

$$t = \frac{d}{\beta\gamma} = \frac{d}{p/m} \equiv g \cdot d\ . \tag{14}$$

the boost factor g is calculated by estimating the B momentum p. This involves the lepton, the charm vertex tracks, a fraction of the electromagnetic energy and the missing total energy. The proper time resolution is given by

$$\sigma_t = \sqrt{g^2\sigma_d + (\sigma_g^2/g^2) \cdot t^2}. \tag{15}$$

The vertex resolution function has a core width of $\sigma_d \approx 400\mu m$, corresponding to about $0.17\,ps$, and the factor σ_g/g in the time-dependent term is below 20 %. From a Monte Carlo simulation, the decay time distributions are obtained for the various lepton sources and parametrized in terms of lifetimes and oscillation parameters.

From the data taken 1990-92, 3008 dilepton events with both $p_\perp > 1\,GeV/c$ are selected. In this sample, 82 % of the leptons originate from a primary $b \rightarrow \ell$ decay, and 13 % are from the cascade decay $b \rightarrow c \rightarrow \ell$.

2550 events have at least 1 proper time measured; for this, a vertex detector hit in both $r\phi$ and z projection is required on the lepton track. A fit of the above-mentioned parametrizations to the measured decay time distribution for these events gives an inclusive b lifetime

$$\tau_b = 1.47 \pm 0.02 ps \tag{16}$$

where the error is statistical only. This preliminary number is in good agreement with the ALEPH single lepton impact parameter measurement [15], but systematically largely independent.

As $B^0\bar{B}^0$ mixing leads to like-sign lepton pairs, the fraction of like-sign events Q should reflect the time dependence of the oscillation. Fig. 3 shows a preliminary measurement of the like-sign fraction as a function of proper decay time. Superimposed is a fit to the data, where the B_d^0 mixing parameter x_d and the B_d^0 lifetime were left as free parameters. The left figure shows the composition of the observed distribution: a constant contribution to the like-sign fraction is due to lepton charge mistagging on the opposite side of the event. A small contribution is expected to originate from lepton misidentification background. The slowly rising behavior of the $b \to c \to \ell$ part is due to the incorrect boost in this case and to the extra charm decay length. The B_s^0 contribution is constant, as maximal B_s^0 mixing was assumed in the fit. The signature for B_d^0 oscillations, the steep rise, is clearly visible. The right figure shows, for comparison, the fit using a time-independent model. This hypothesis is rejected at 99% C.L. The extraction of the oscillation frequency will be possible after further studies of potential systematic effects.

Together with the measurement of the D^*-lepton charge correlation, this represents the first observation of particle-antiparticle oscillations in time, outside the neutral kaon system.

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