Oscillations of neutral B mesons systems

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Abstract
The oscillation phenomenon in the neutral B mesons systems is now well established. The motivations and principles of the measurements are given; then the most recent results from the LEP experiments, the CDF collaboration at Fermilab and the SLD collaboration at SLAC are reviewed. The present world average of the $B^0_d$ meson oscillation frequency is $\Delta m_d = 0.471 \pm 0.016\,\text{ps}^{-1}$ and the lower limit on the $B^0_s$ oscillation frequency is $\Delta m_s > 12.4\,\text{ps}^{-1}$ at 95% CL.

Review talk given at the
Third International Conference on Hyperons, Charm and Beauty Hadrons,
Genoa, Italy, 29 June - 3 July 1998
1 Physics motivations

It is known since a long time that $B_0^d(d\bar{b})$ and $B_0^s(s\bar{b})$ mesons can undergo particle-antiparticle mixing, due to second-order weak interactions which involve box diagrams. If CP violation is neglected, the CP eigenstates of the $B^0 - \overline{B^0}$ system are also mass eigenstates and the probability that a purely $B^0$ state produced at time $t=0$ will decay as a $B^0$ or $\overline{B^0}$ at time $t$ is:

$$p(t, \mu) = \frac{e^{-t/\tau}}{2\tau} \left[ 1 + \mu \cos(\Delta m t) \right]$$

The oscillation frequency $\Delta m$ is the mass difference between the two mass eigenstates, $\tau$ is the average lifetime and $\mu = +1$ (resp -1) if the final state is a $B^0$ (resp $\overline{B^0}$).

In the framework of the Standard Model, $\Delta m$ may be computed with a rather large uncertainty coming from QCD correction factors. The ratio of the oscillation frequencies is under better control:

$$\frac{\Delta m_s}{\Delta m_d} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \left| V_{ts} \right|^2$$

where $\xi = 1.16 \pm 0.10$ contains all theoretical uncertainties. Therefore the measurement of $B_0^d$ and $B_0^s$ oscillation frequencies should give constraints on the poorly known CKM matrix elements $V_{ts}$ and $V_{td}$. These constraints are conveniently expressed in the framework of the Wolfenstein parametrisation of the CKM matrix, introducing the so-called Unitarity Triangle.

2 Experiments and data

2.1 LEP experiments

The four LEP experiments ALEPH, DELPHI, L3 and OPAL use data taken at the $Z$ peak from 1991 to 1995. They have accumulated about 4 million hadronic $Z$ decays each, i.e. about one million pairs of $B$ mesons, with the following properties:

- $B$ mesons are produced with a large boost (mean momentum around 35 GeV/c), giving a decay length around 2 to 3 mm;

- All experiments have good Silicon vertex detectors and obtain a resolution on the decay length around 300 micrometers;

- The particle identification, which is very important for $B_s^0$ studies, is done through $dE/dx$ measurements in ALEPH and OPAL, and using a RICH (Ring Imaging Cerenkov counter) in DELPHI.

2.2 CDF

The Collider Detector Facility at Fermilab has collected 130 pb$^{-1}$ of $p\overline{p}$ collisions at centre of mass energy 1.8 TeV since 1992. At the Collider there is a huge $B$ meson
production rate, with a huge background. The B mesons are produced with a boost which is less favourable than at LEP/SLC (mean momentum around 15 GeV/c).

2.3 SLD

The SLD collaboration at SLAC has taken around 500000 hadronic Z0 decays between 1993 and 1997, 350000 of which are analyzed. The excellent performances of the SLD vertex detector allow a much better decay length resolution than LEP experiments (around 50-100 micrometers). In addition, the electron beam polarisation may be used as a powerful tool for the B meson tagging [1]. The particle identification is done using a Ring Imaging Cerenkov counter.

3 Time-dependent oscillation measurements

All analyses require reconstruction of the decay time of the B^0 mesons. This is done by the measurement of the decay length and of the momentum of the B^0. As it is impossible to describe in detail all existing measurements, only the basic principles are given in this section.

3.1 B^0 meson identification

The B^0 meson is in general identified by the detection of a high energy, high Pt lepton.

Inclusive lepton analyses demand that this lepton has a large impact parameter with respect to the interaction point. This gives several tens of thousands of events, but with a low purity (e.g. 10% for the B^0_s).

In addition, one can search for the exclusive decay of a charmed meson. For instance for B^0_d decays one looks for a D^*-l^+ final state, with D^*^- → D^0π^-; the D^0 meson is then searched for via its hadronic decays e.g. K^-π^+. For B^0_s decays one looks for a D^-_s^-l^+ final state, then for D_s hadronic decays such as φπ. The charmed meson is used together with the lepton to reconstruct the B^0 decay vertex; then the decay length is computed from this vertex and the event interaction point. These semi-exclusive analyses give some hundreds of events per experiment, with a purity which may be as high as 50%.

In a recent analysis DELPHI [2] reconstructs fully hadronic decays of the B^0_s. This gives some tens of events, with a very high purity.

3.2 Decay time measurement and error

The B^0 boost is computed using the lepton, the reconstructed charmed meson and, when possible, the neutrino energy estimated from the missing energy. Typical values of the decay time resolution for LEP experiments are around 0.3 ps for inclusive lepton analyses, 0.15 ps for charm-lepton analyses, and 0.06 ps for the DELPHI exclusive B^0_s reconstruction. SLD obtains a resolution of 0.06 ps for D_s l events.
3.3 Tagging of the $B^0$ at decay

One has to know if the detected $B^0$ meson has oscillated or not before decaying; therefore it is necessary to tag it both at production and at decay time.

The tagging of the $B^0$ at decay time is obtained simply by the charge of the energetic lepton, since e.g. a positive lepton $l^+$ is the signature of the decay of a $B^0$ meson. This final state tagging is not perfect since one may detect a lepton from a $b \rightarrow c \rightarrow l$ decay; the corresponding mistag probability is computed from simulated events.

3.4 Tagging of the $B^0$ at production

This is much more complicated. Usually one divides the event in two opposite hemispheres defined with respect to the event thrust axis; several tags are used in each hemisphere:

- In the $B^0$ hemisphere, the nature and the charge of the most energetic fragmentation track carries information on the production state of the $B^0$ meson: e.g. an energetic $K^+$ is produced in association with a $B^0$. One can also use the sign of the jet charge in this hemisphere.

- In the hemisphere opposite to the detected $B^0$, several tags may be used. First, one can search for an energetic lepton with large $P_T$ and impact parameter. One can also use the jet charge of the hemisphere. The sign of the lepton and of the jet charge indicate if a $b$ or $\bar{b}$ quark was produced in this hemisphere.

This initial state tagging is far from being perfect. There are experimental difficulties: particle misidentification, incorrect attribution of a charged track to the primary vertex, etc., and possible mistags due to physics: the $b$ quark in the opposite hemisphere may give a $B^0$ meson which may oscillate before decay, or the detected lepton may come from the decay of a charmed hadron. All these mistag probabilities must be carefully computed using the simulation.

4 Results

There are presently about 35 different time-dependent $B^0$ oscillation analyses, some of them being presented for the first time at this conference. The oscillation frequency is fitted from a likelihood fit to the complicated decay probability function which includes all the tags, mistag probabilities and efficiencies coming from detailed Monte Carlo studies.

4.1 Measurement of $\Delta m_d$

Four new measurements are available since the 1997 Summer conferences:

- one from CDF [3], using $Dl$ and $D^*l$ correlations with the following result:
\[ \Delta m_d = 0.471^{+0.078}_{-0.068} \text{(stat)} \pm 0.034 \text{(syst)} \text{ ps}^{-1} \]  
(3)

- from L3 \([4]\), three analyses using lepton-lepton decay length, lepton-jet charge and lepton-lepton impact parameter, giving:

\[ \Delta m_d = 0.444 \pm 0.028 \text{(stat)} \pm 0.028 \text{(syst)} \text{ ps}^{-1} \]  
(4)

These new results are combined with all the previously published ones, resulting in an average of 24 \( \Delta m_d \) measurements:

\[ \Delta m_d = 0.477 \pm 0.017 \text{ ps}^{-1} \text{ (preliminary)} \]  
(5)

This average may be combined with the time-integrated mixing measurements made by CLEO and ARGUS at the \( \Upsilon_{4S} \) resonance, giving the following world average:

\[ \Delta m_d = 0.471 \pm 0.016 \text{ ps}^{-1} \text{ (preliminary)} \]  
(6)

This world average is now dominated by systematics (0.013 ps\(^{-1}\) systematic error, whereas the statistical error is 0.010 ps\(^{-1}\), at the 2\% level).

Figure 1 gives the average of the measurements of \( \Delta m_d \) obtained by each experiment.

### 4.2 Limits on \( \Delta m_s \)

From Eq. (2), the \( B^0_s \) oscillation frequency is expected to be about 20 times greater than that of the \( B^0_d \). As the \( B^0_s \) meson production rate is about 1/4 that of the \( B^0_d \), the search for \( B^0_s \) oscillations is therefore an experimental challenge. Up to now, no measurement of \( \Delta m_s \) is available; only lower limits are obtained from 11 existing analyses.

At this conference, the results described below have been presented for the first time. All limits given below are 95\% Confidence Level limits.

- DELPHI \([5]\) has presented a new limit using 280 \( D_s \ell \) events, the \( D_s \) being reconstructed in 6 hadronic and 2 semileptonic decay modes. They obtain a lower limit of \( \Delta m_s > 7.4 \text{ps}^{-1} \).

- DELPHI \([2]\) gives a lower limit of \( \Delta m_s > 2.4 \text{ps}^{-1} \) from fully reconstructed \( B^0_s \) mesons (they have 17 \( \pm 8 \) events reconstructed in 8 decay channels). These events give an important contribution for high \( \Delta m_s \) values (above 10 ps\(^{-1}\)) due to their excellent proper time resolution.

- SLD \([1]\) has presented three analyses: lepton - D , charged dipole, lepton + tracks. They exclude the following regions:

\[ \Delta m_s < 1.3 \text{ ps}^{-1} \text{ and } 2.7 < \Delta m_s < 5.3 \text{ ps}^{-1} \]  
(7)

- CDF \([6]\) has presented 1068 \( \pm 70 \) events with \( \phi \ell \) correlations, from which they obtain a lower limit of \( \Delta m_s > 5.8 \text{ps}^{-1} \).
At the time of the conference, the overall combination could not yet be done. This has been done since that time by the LEP Working Group, using the method defined in \[7\]. The resulting preliminary world average of the amplitudes is displayed in Figure 2, and the preliminary lower limit is \(\Delta m_s\):

\[
\Delta m_s > 12.4 \text{ ps}^{-1} \text{ at } 95\% \text{ CL (8)}
\]

with a sensitivity of 13.8 ps\(^{-1}\).

5 Consequences on the Unitarity Triangle

F. Parodi et al. \[9\] have studied the consequences of the above results for the Unitarity Triangle. They find rather strong constraints on the triangle apex position: \(\rho = 0.189 \pm 0.074\), \(\eta = 0.354 \pm 0.045\) and also a strong constraint on the \(\beta\) angle: \(\sin(2\beta) = 0.73 \pm 0.08\). This is especially interesting before the starting up of the B-factories at SLAC and KEK, which will measure this angle directly.

They find also that within the present knowledge of all parameters, the allowed range of \(\Delta m_s\) is \(6 < \Delta m_s < 21\text{ps}^{-1}\) at 95\% CL. This means that half of the allowed range is already experimentally excluded.

6 Future prospects

The most recent individual measurements of the \(B_0^0\) oscillation frequency from L3 and CDF are impressively precise. However the present world average has a precision around 3\%, and therefore future improvements are expected to be modest.

The limit on \(\Delta m_s\) should improve appreciably in the near future. The LEP experiments still have room for improvement, especially ALEPH and OPAL. SLD should also give new limits using their full statistics on tape and CDF will give more results on their present data using new channels.

In a more distant future (2 years), new results should come from SLD if they run in 1999 (expected sensitivity around 20 ps\(^{-1}\)). In year 2000, the HERA B experiment at DESY will have data, and at the Fermilab Collider the CDF and D0 collaborations will collect new data with an expected sensitivity of 25 ps\(^{-1}\). This would explore the full domain allowed to \(\Delta m_s\) by the Standard Model.
7 Conclusions

Using the most recent CDF and L3 measurements, the $B_0^0$ oscillation frequency is now measured with an accuracy of almost 3%:

$$\Delta m_d = 0.471 \pm 0.016 \text{ ps}^{-1} \text{(preliminary)} \quad (9)$$

New analyses on the $B_s^0$ oscillation frequency give the following combined new lower limit:

$$\Delta m_s > 12.4 \text{ ps}^{-1} \text{ at 95\% CL (preliminary)} \quad (10)$$

This result excludes already half of the allowed region for $\Delta m_s$ in the Standard Model, and gives efficient constraints on the Unitarity Triangle. Improvements on the $\Delta m_s$ limit are expected from updated LEP analyses and from new data at SLD and at the Fermilab Collider.

8 Acknowledgements

I would like to thank the Third International Conference on Hyperons, Charm and Beauty Hadrons to have invited me for this talk.

I also wish to thank the various people who provided me with the results of all collaborations: O. Schneider (ALEPH), B. Wicklund (CDF), A. Stocchi (DELPHI), V. Andreev (L3), M. Jimack (OPAL) and S. Willocq (SLD). I also thank warmly the LEP Working Group on B oscillations for providing me with Figures 1 and 2, and A. Stocchi for the constraints on the Unitarity Triangle \[.].
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Figure 1: Average $\Delta m_d$ value per experiment. This figure has been provided by the LEP Working Group on B Oscillations [8].
Figure 2: Combined $B^0$ oscillation amplitude spectrum as a function of $\Delta m_s$. A 95% CL lower limit of 12.4 ps$^{-1}$ on $\Delta m_s$ is derived from this spectrum. All published or preliminary results known as of July 13th 1998 are included in this figure, provided by the LEP Working Group on B Oscillations [8].