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BEAUTY MIXING AND LIFETIMES AT LEP

A. ROUSSARIE

Talk given at
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BEAUTY MIXING AND LIFETIMES AT LEP

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Abstract

Experimental LEP results concerning the mixing and lifetime of B hadrons are reviewed and averaged, including a few results from other colliders. The $B-\bar{B}$ mixing is described and various time integrated and time dependent measurements are presented, giving the following results:

- B_d^0, B_s^0 average : $\chi = 0.1241 \pm 0.0068$
- B_d^0 : $\chi_d = 0.175 \pm 0.018$ or $\Delta m_d = 3.16 \pm 0.25 \cdot 10^{-4}\mathrm{eV}/c^2$
- B_s^0 : $\chi_s > 0.43$ or $\Delta m_s > 12. \cdot 10^{-4}\mathrm{eV}/c^2$ (95% C.L.).

The fraction of B_s produced in the b quark hadronisation is derived: $f_s = 0.113\,^{+0.027}_{-0.026}$.
The different techniques used to extract the B lifetimes (average and exclusive) are discussed and the following averages are obtained :

Averaged B	:	1.533	$\pm$	0.022 ps
B_u^+	:	1.62	$\pm$	0.10 ps
B_d^0	:	1.50	$\pm$	0.10 ps
B_s^0	:	1.49	$\pm$	0.15 ps
Λ_b	:	1.10	$\pm$	0.14 ps

The observed hierarchy, except may be for a rather low value of the Λ_b lifetime, follows the theoretical expectations successfully experienced in the charm sector.

Talk given at "Les Rencontres de Physique de la Vallee d'Aoste",
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1 Introduction

The study of B hadrons properties is a very important and active field.

The first motivation is the knowledge of the electroweak couplings of quarks, parametrized in the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements. The B lifetime and the semileptonic branching fraction $b \rightarrow cl\nu$ depend on V_{cb} . The B_d^0 (resp. B_s^0) mixing is related to the V_{td} (resp. V_{ts}) matrix element.

The second motivation is linked to the strong interaction. The possibility to measure the exclusive lifetimes of individual hadron states (B_u^+ ,B_d^0 ,B_s^0 and Λ_b) allows to see what are the effects of the strong interaction between quarks in the B decays. They have been measured to be very important in the charm sector.

The phenomenology of the $B - \bar{B}$ mixing is first briefly discussed. Methods to tag the b quark charge are listed. Results on time integrated and time dependent measurements of the $B - \bar{B}$ mixing parameters are given and averaged. They allow a model independent determination of f_s , the fraction of B_s^0 mesons produced in the hadronisation of a $\bar{b}$ quark. Then, the numerous determinations of the averaged B lifetime and of the four individual lifetimes are given and averaged. They are compared to theoritical expectations.

Prospects of the precision that LEP will allow on these measurements, by the end of the Z^0 running, are given for both mixing and lifetimes.

2 $B - \bar{B}$ mixing measurements

2.1 Theoretical motivations

The possibility of B mixing is formally described in the same way as the well known $K^0 - \bar{K}^0$ mixing [1]. It originates from the non diagonality of the B mass matrix. Therefore the B^0 mass eigenstates, B_1 and B_2 are linear combinations of the weak eigenstates B^0 and $\overline{B^0}$. From their mass difference $\Delta m = m_1 - m_2$, they get a different time evolution, creating an oscillation from a weak eigenstate to the other. For an initially pure B^0 state, the probability of observing, after a time t, a $\overline{B^0}$ state is

$$Prob(B^0 \rightarrow \overline{B^0}) = \frac{1}{2}e^{-\Gamma t}(1 - \cos \Delta m t).$$

where the widths of the two states have been assumed equal. The total (time integrated) probability of mixing $B^0 \rightarrow \overline{B^0}$, obtained by integration, is

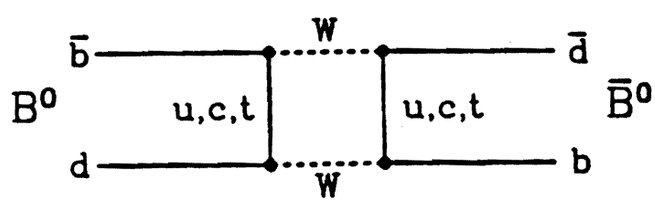

Figure 1: Box diagram allowing the transition $B^0 \rightarrow \overline{B^0}$ in the Standard Model.

$$\chi = \frac{1}{2} \cdot \frac{x^2}{1+x^2},$$

where the mixing parameter $x = \frac{\Delta m}{\Gamma}$ is the oscillation frequency expressed in terms of the lifetime. χ varies between 0 (no mixing) and 0.5 (maximal mixing for large Δm).

In the Standard Model, the B^0 to $\overline{B^0}$ transition occurs via the second-order W-exchange diagrams (box diagrams as illustrated in Figure 1) which have been calculated. Those involving the top quark exchange dominate. For simplicity we recall their dependence upon the top quark mass and the CKM matrix elements:

$$\Delta m_q \propto m_t^2 |V_{tq}|^2$$

where $q = d, s$ for the B_d^0 and B_s^0 respectivly. The proportionality factor, involving phase space factors, QCD correction factors and the B meson decay constant, is estimated with an accuracy not better than 20%. In the ratio $\Delta m_s/\Delta m_d \propto |V_{ts}/V_{td}|^2$, these uncertainties compensate partly and the proportionality factor is close to one. From what is known of the CKM matrix we obtain the limit $\Delta m_s/\Delta m_d \geq 8$. More elaborate fits [2] involving all available measurements and QCD lattice computations predicts this ratio to lie in the range 8 to 22 (13 most likely), for a top quark mass of 150 Gev.

The $B - \bar{B}$ mixing parameters χ can be measured using the fact that, either in hadron or in electron colliders, B mesons are pair produced. The charge of both b quarks can be measured by several means: jet charge or charge of a decay product: lepton, charm or strange. The mixing parameters are extracted from the study of the correlation between the two charges measured in opposite hemispheres. The b quark charge tagging can be done independently or not of the decay time of the B hadron, allowing time integrated or time dependent measurements. For the B_s^0 hadron, x_s being expected large, only the second type of measurement will be usefull.

2.2 Time integrated $B - \bar{B}$ mixing

The experiments performing these measurements are of two classes: Those running at high energy colliders (LEP, PEP, S$p\bar{p}$S, TEVATRON) produce all B hadrons, and those done at e^+e^- colliders on the $\Upsilon(4S)$ resonance (CESR and DORIS), close to the $b - \bar{b}$ threshold produce only B_u^+ and B_d^0 mesons. The first class of experiments measures $\chi = f_s\chi_s + f_d\chi_d$ where f_s and f_d are respectively the fraction of B_s^0 and B_d^0 mesons produced in the hadronisation of a b quark. The second class obtains χ_d.

2.2.1 High energy measurements of χ

For this class of measurements, the fraction of like-sign events is given by $2\chi(1-\chi)$. LEP results will be given first, then older hadron collider results will be recalled.

From LEP, the most precise results come from dilepton analyses. Events with two leptons produced in opposite hemispheres are considered. Selecting on high values of the lepton momentum (p) and transverse momentum (p_t) with respect to the jet axis, give very good purities in $B - \bar{B}$ events. By cutting p and p_t at 3 and 1.25 Gev/c respectively, Aleph obtains a purity of 99.6%. In 12.4% of these events one lepton comes from a $b \rightarrow c \rightarrow l$ cascade.

Experiment	Ref	Year of data	χ
OPAL	6	90-91	$0.143\ ^{+0.022}_{-0.021} \pm 0.007$
L3	7	90-92	$0.118 \pm 0.012 \pm 0.010$
DELPHI	8	90-92	$0.121 \pm 0.016 \pm 0.004 \pm 0.004$
ALEPH	9	90-93	$0.1059 \pm 0.0073 \pm 0.0080\ ^{+0.0047}_{-0.0054}$
LEP, Dileptons average			0.1167 ± 0.0078

Table 1 : **χ mixing parameter**, averaged on B_d^0 and B_s^0 mesons, measured at LEP, using dilepton events. The third error given for Delphi and Aleph is the modelling error.

Experiment	Ref	Year of data	κ	c	χ
ALEPH	11	90	0.5	0.72 ± 0.03	$0.128 \pm 0.018 \pm 0.027$
DELPHI	12	91-92	0.6	0.91 ± 0.05	$0.149 \pm 0.014\ ^{+0.017}_{-0.011}$
LEP, Lepton-jet average					0.145 ± 0.017

Table 2 : **χ mixing parameter**, averaged on B_d^0 and B_s^0 mesons, measured at LEP using lepton-jet events. The jet charge is computed by weighting the track charges by their momentum to a power κ. The measured mixing parameter $f_d\ \chi_s + c\ f_s\ \chi_s$ (c given above) is corrected to get $\chi = f_d\ \chi_s + f_d\ \chi_s$ by using $f_s = 0.113^{+0.028}_{-0.026}$ and $\chi_s = 0.49^{+0.01}_{-0.035}$ (see text).

It is a dangerous background because the tagging charge is reversed. The main systematic error comes from the uncertainty on the branching fraction of this mode. All four LEP experiments have obtained results. They are given in table 1 (the data collection period is indicated). Since the 1993 summer, only Aleph and Delphi have updated their result for this conference. The average of table 1 results is $\chi = 0.1167 \pm 0.0078$.

The second type of measurements is obtained from the LEP experiments by selecting single lepton events. In the hemisphere opposite to the lepton, the jet charge is estimated from the momentum-weighted average (by a given power κ) of the track charges. This charge retains some discrimination between b and $\bar{b}$. Due to a different sensitivity of the jet-charge to B_d^0 and B_s^0 decays, the measured quantity is $f_d\chi_d + Cf_s\chi_s$, where the value of C is determined from the simulation. Two experiments (Aleph and Delphi) have obtained results, already published last year. Their precision is limited by systematical errors due to the calibration of the jet charge. They are given in table 2. The values of κ and C are given. The published values have been corrected by $(1-C)f_s\chi_s$ to get the result for χ given in the table. We have used the values of f_s and χ_s coming from a compilation obtained later in this presentation.

A third type of measurement done at LEP by Delphi is the study of the lepton-Λ charge correlation [10]. The statistics being small (279 events), the result is less precise than the previous measurements by a factor 5. It gives

$$\chi = 0.129^{+0.075}_{-0.065} \pm 0.036(syst) \pm 0.025(MCstat)$$

Experiment	Ref	Year of data	Data	χ
UA1	3	84-89	$\mu\mu$	$0.148 \pm 0.029 \pm 0.017$
CDF	4	≤ 91	ee, $e\mu$	$0.176 \pm 0.031 \pm 0.032$
D0	5			$0.140 \pm 0.030 \pm 0.060$
COLLIDER average				0.156 ± 0.025

Table 3 : χ **mixing parameter**, averaged on B_d^0 and B_s^0 mesons, measured at $p\bar{p}$ colliders.

Hadron colliders experiments have studied high p_t isolated dileptons events. It was the first opportunity to measure χ. These results are well known and their description falls out the scope of this talk. They are given in table 3. They average to $\chi = 0.156 \pm 0.025$.

Therefore the global average of χ from high energy experiments is

$$\chi = 0.1241 \pm 0.0068$$

2.2.2 $\Upsilon(4S)$ measurements of χ_d

The conditions are quite different. Near threshold only B_u^+ and B_d^0 states are produced. The measurement is only sensitive to χ_d. In addition the charge conjuguaison conservation requires that only a B_d^0 pair or a B_u pair is produced. The extraction of χ_d. requires the knowledge of branching fractions. This difficulty is overcomed in certain measurements by tagging D^*-lepton events where the D^* charge tags the B charge. In that case the systematical error is lowered while the systematical one is decreased. All these measurements are not the subject of this talk. We just recall the χ_d average obtained from the $\Upsilon(4S)$ measurements, as given at the Marseille conference [13],

$$\chi_d = 0.158 \pm 0.026$$

2.3 Time dependent $B - \bar{B}$ mixing

The principle of a time dependent mixing measurement is to look at the decay time dependence of the charge correlation. It can only be done at high energy (LEP for the moment) where a necessary boost of the B meson is provided. On one side, the charge measurement (lepton or jet charge) signs the time integrated B charge. If corrected by the global mixing χ (if a charge $+1$ is observed, it corresponds statistically to a charge $1-2\chi$) it gives the charge at the time $t = 0$ in this hemisphere and consequently the charge in the opposite hemisphere. On the other side, the B meson decay vertex is observed using the nice vertexing capabilities of the LEP apparatus. The decay time and the charge at this time are measured. The correlation between the two charges (at $t = 0$ and at decay time) is examined as a function of the decay time, and the oscillation frequency Δm_d is measured. The oscillation amplitude

depends on the purity in B_d^0 of the selection, the cleaness of the tagging (the tagging charge can be reversed by mixing or background) and the decay time resolution.

Four measurements of Δm_d have been performed. The results are given in table 4. They differ by the way events are selected, the charges are signed and the decay time is measured.

• In the first measurement, Aleph [14], has selected dilepton events (91-92 data, 1577 dilepton events of which 902 have decay times measured on both sides). A clean hadron secondary vertex is searched ("charm" vertex) on the side of each lepton. A "charm"-lepton vertex is tried. If successfull it is the "B " secondary vertex. It's distance to the primary vertex is the decay lenght. Then the B momentum is reconstructed from the charged and neutral energies measured in the lepton-"charm" system and corrected for detector effects. Lenght and momentum are converted to a decay time. The B lifetime can be extracted from the decay time distribution. This allows to check if the distance and momentum resolutions are well appreciated. The correlation between the 2 lepton charges displays a nice oscillation (see Ref 14). The result depends on the fractions of B and background contained in the sample and of the B_d^0 specific lifetime, all numbers which have been have been varied within acceptable ranges. The measured Δm_d value is given in table 4. In addition a short period oscillation, originating from the B_s^0 mixing has been searched. A 95% confidence level limit of $12. \cdot 10^{-4} eV/c^2$ has been placed on Δm_s . Using the B_d^0 lifetime value compiled later, it can be converted in the limit $x_s \geq 2.5$ (95% C.L.).

• Delphi has submitted at this conference an analysis of dilepton events, similar to the one of Aleph. They measured only Δm_d (see table 4).

• Aleph has published another determination of Δm_d [15], using 91 and 92 data. It uses a selection of 284 events containing a $D*^+ \rightarrow \pi^+ D^0$ decay on one side (the D^0 is observed through $K^+\pi^-, K^+\pi^+\pi^0 or K^+\pi^+\pi^-\pi^-$ decays) and a lepton on the other side. The time information is restricted in that analysis to the measurement of the distance of the D^* vertex to the primary vertex, which sums the B and D^0 decay distances (dominated by the B distance). They have demonstrated that for a large oscillation period, this is precise enough to measure correctly the oscillation parameter from the study of the variation of the $D^* lepton$ charge correlation with the distance. The result is given in table 4. The events being purer in B_d^0 decays, the systematical error is smaller than in the previously described Aleph measurement, while the statistical is larger.

• The last available measurement of Δm_d , presented by Opal at this conference, shows some interesting original points. Using also the 1993 data (1.9 millions hadronic Z^0 events) they make use simultaneously of several tagging methods listed above. The selection requires on one side the observation of a D^*-lepton pair of opposite charge. 426 such events are selected where the decay $D*^+ \rightarrow \pi^+ D^0$ is followed by the D^0 decay in $K^+\pi^-$ or $K^+\pi^+\pi^0$. The purity in B_d^0 of this selection is particularly high (the B_u^+ over B_d^0 fraction is 16%). The same sign pairs are used to monitor and substract the background which amount to 27%. The D^*-lepton vertex is well measured making the vertexing resolution (distance and boost) excellent (the relative accuracy on the decay time ranges from 16% to 20%). On the other side the $t = 0$ charge is measured using the jet charge technics. Some additional information is obtained on this charge by measuring also the global charge of the D^*-lepton hemisphere. The fact that the B_d^0 has mixed or not does not affect this charge. Using only the opposite hemisphere charge, the $t = 0$ charge tagging is reversed in 35% of all cases. This mistagging probability drops to 28% if the additional information is used. The correlation between the two hemispere charges is displayed versus the decay time in figure 2. The observed oscillation

is (too naïvly?) fitted by a sinusoid. The Δm_d result given in table 4 has the best accuracy

Avering the four results of table 4 we get the LEP average

$$\Delta m_d = (3.386 \pm 0.352) \cdot 10^{-4} eV/c^2$$

This LEPresult on the B_d^0 mixing can be compared to the result of section 2.2.2, obtained from the time-integrated mesurement of χ_d, at the $\Upsilon(4s)$. The relation $x_d = \Delta m_d \cdot \tau_{B_d^0}/\hbar$ and the relation between x_d and χ_d of section 2.1 permit this comparison, in which we use for the value of τ_B the compiled value of the average B lifetime given later. The result is given in table 5. Comparable accuracies are already achieved in the two measurements.

2.4 f_s determination

A model independent determination of f_s, the fraction of B_s^0 mesons produced in the hadronisation of a b quark can be derived from the mixing parameter measurements given above :

- B_d^0 : $\chi_d = 0.175 \pm 0.018$
- B_s^0 : the 95% confidence level limit $x_s > 2.5$ can be converted in the value $\chi_s = 0.49\ ^{+0.01}_{-0.03}$ where the central value corresponds to a high value of x_s (7) and the upper error takes care of the limit, $\chi_s < 0.5$.
- Average $B_d^0 - B_s^0$: $\chi = f_s\chi_s + f_d\chi_d = 0.1241 \pm 0.0068$.

If we define f_d, f_u, f_s, and f_{bar} the fraction of B_d^0, B_u^0, B_s and Λ_b hadrons produced in the hadronisation, we have the relations:

- $f_d + f_u + f_s + f_{bar} = 1$
- $f_u = f_d$ from SU_3 symetry.

At this point we input an educated guess for the baryon fraction, $f_{bar} = 0.10 \pm 0.04$, which covers the assumed domain. We can solve the above equations and get:

$$f_s = 0.113\ ^{+0.027}_{-0.026}$$

The part of the f_s uncertainty coming from the assumed error on f_{bar} is only 0.009. The value obtained for f_s is in good agreement with low energy determinations measuring the production of strange particles in hadronic events.

Experiment	**Ref.**	**method**	**Year of data**	$10^4 * \Delta m_d$ (eV/c^2)
ALEPH	14	ℓ - ℓ	91-92	$3.3\ ^{+0.5}_{-0.4} \pm 0.7$
ALEPH	15	ℓ - D^*	91-92	$3.44\ ^{+0.65}_{-0.70}\ ^{+0.26}_{-0.20}$
DELPHI	16	ℓ - ℓ	91-92	$3.49\ ^{+0.72}_{-0.66}\ ^{+0.72}_{-0.66}$
OPAL	17	Jet-ℓ D^*	90-93	$3.36 \pm 0.50 \pm 0.16$
LEP average				3.386 ± 0.352

Table 4 : B_d^0-$\bar{B}_d^0$ mass difference measured at LEP from time dependant oscillations. The methods are explained in the text.

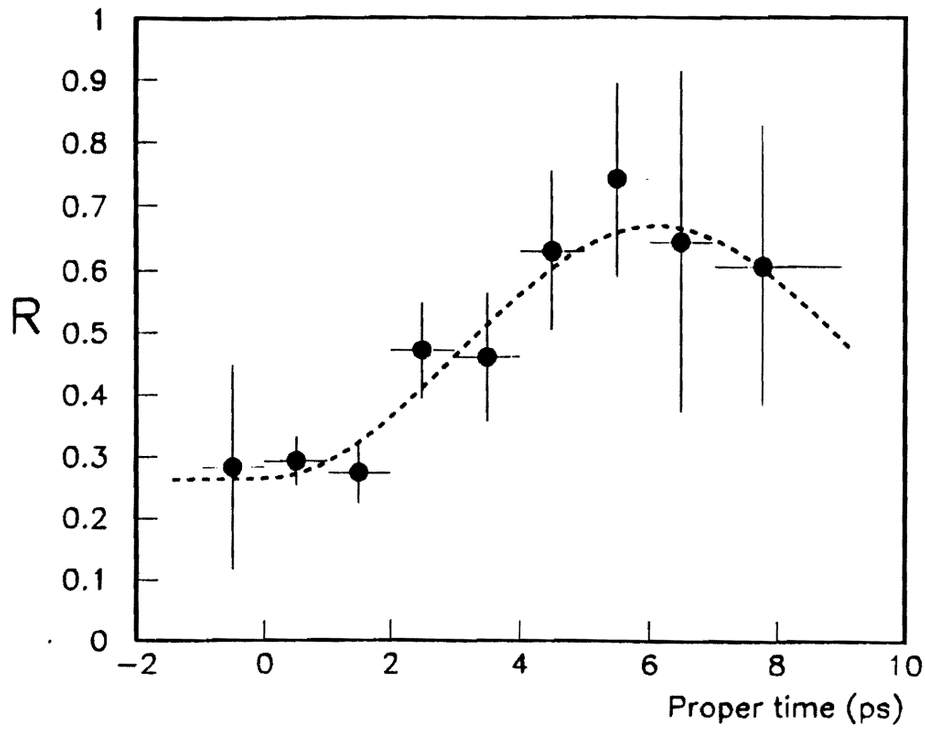

Figure 2: OPAL preliminary B_d^0, time dependent mixing measurement: Ratio of mixed to total events as a function of proper decay time. Overlaid is the fit result.

Origin	$10^4 \times \Delta m_d$ (eV/c^2)	x_d	χ_d
LEP	3.386 ± 0.352	$0.788 \pm 0.082 \pm 0.011$	$0.191 \pm 0.025 \pm 0.003$
Υ $(4S)$	$2.924 \pm 0.352 \pm 0.042$	0.681 ± 0.082	0.158 ± 0.026
Average	3.157 ± 0.250	0.735 ± 0.058	0.175 ± 0.018

<u>**Table 5**</u> : **B_d^0 mixing parameters.** LEP measures Δm_d (time dependant measurements) and $\Upsilon(4S)$ machines (CLEO and ARGUS) measures χ_d. The conversion from one to the other is done using the average B lifetime compiled in this rapport ($\tau_B = 1.533 \pm 0.022$ ps). The second error, if any, comes from the error on τ_B.

2.5 Prospect of B_s^0 mixing measurements at LEP100

It is interesting to give some hints, derived from our present knowledge, on the prospect of measuring the B_s^0 mixing parameter x_s at LEP. We have presented a 95% C.L. lower limit from Aleph, $x_s > 2.5$, based on 1 million Z. The x_s limit scales as the square root of the number of Z. This determination uses only one search for fast time oscillations in dilepton events. We know from preliminary homeworks that other methods will be as powerfull. If we count 4 methods, it gains a factor 2. We are four LEP experiments, may be 3 have the power to do high precision time measurements ($\sqrt{3}$ gain). Counting on 4 millions Z events by the end of the LEP100 running, leads to a reachable limit of 17 on x_s.

3 Lifetime measurements

We start this section by describing briefly the various classes of lifetime measurements performed at LEP, impact parameter or proper time. Then two types of lifetimes will be determined: the average B lifetime or the exclusive B lifetimes, depending if the event selection averages or not on the differents B species (B_u, B_d B_s or Λ_b). In the two cases, the physic's motivation will be first given.

3.1 Experimental methods of lifetime measurements

A large variety of experimental techniques are used to measure lifetimes. Some general principles they follow are indicated bellow. Two general classes of method can be distinguished :

• Impact parameter measurements : They consist of measuring the distance δ of cloasest approch of a B decay product (in general a lepton) to the primary vertex. This distance is signed such as it is positive if the apparent decay lenght with regard to the jet axis is positive. The track impact parameter depends on the transverse momentum given by the decay. It is therefore largely independent of the boost of the B hadron, but its distribution must be related to the lifetime through a Monte Carlo simulation and convoluted with the resolution. The δ resolution is of the order of 25μ for LEP experiments which include a precise silicon vertex detector (Aleph, Delphi). It is respectively 50μ and 100μ for Opal and L3.

The measurements of this first class allow high statistics but they cannot, in general discriminate B species.

• Proper time measurements : In this class, the B vertex is reconstructed and its distance to the primary vertex, L_{decay}, measured. This type of measurement is much helped by a high precision vertexing provided by a silicon vertex detector. Several methods are used to build the B vertex. 1) : a fully recognized charmed hadron vertex is selected by spectroscopy. The charm track they form is vertexed with another B decay leading track (lepton or hadron). 2) : an inclusive production of a resonance coming promptly from the B decay is looked for (ex $J/\psi \rightarrow \ell^+\ell^-$). 3) : clean, well separated secondary vertices are formed with the observed charged tracks. They mix the B and D vertex but, the charm lifetime being small, the measured vertex is a good estimate of the B vertex. Decay lenght resolutions between 200 and 300μ (for an averaged decay lenght of 2500μ) are currently achieved by Delphi and Aleph.

The proper time is measured, on an event by event basis, by computing the ratio of the decay lenght to the B momentum which is measured using three methods : 1) The b quark fragmentation being hard, the B momentum can be assumed to be constant. Only the decay lenght is used to determine the lifetime. 2) A better method is to built a jet "around" the tracks concidered by the vertexing algorithm (ex $J/\psi \rightarrow \ell^+\ell^-$), limiting it's mass to a value close to the B mass. 3) The best method apply in the study of semileptonic B decays where the charm hadron is fully recognized. The B momentum is obtained by summing the charm and lepton momenta and possibly the neutrino momentum computed from the missing energy in the lepton hemisphere (Aleph). Depending on the method, the B momentum resolution varies from 7% to 25% and is carefully monitored using the simulation.

3.2 Average B lifetime

3.2.1 Theoretical motivations

The spectator model of B decays is expected to dominate. The B decay is due to the heavy quark transition $b \rightarrow cW^-$, the light quark playing no role (spectator). Therefore the partial width of the semileptonic decay can be computed from the CKM matrix element V_{cb} :

$$\Gamma(b \rightarrow \ell X) = K\,|V_{cb}|^2$$

where K is a factor which depends on the b quark mass (to the fifth power), on phase space factors and QCD corrections. It can be predicted with a model dependent accuracy not better than 20%. $\Gamma(b \rightarrow \ell\ X)$ is computed as the ratio of the semileptonic B branching fraction (known to a relative accuracy of 3%) to the averaged B lifetime τ_B . V_{cb} derives from the equation :

$$|V_{cb}|^2 = \frac{Br(b \rightarrow \ell\ X)}{K \cdot \tau_B}$$

With last year's results (the mondial average of the τ_B resolution was 2.6%), the accuracy on V_{cb} was already limited to 10% by the model determination of K. Newer measurements, based on the application of heavy quark effective theories are expected to give, with improved statistics, a better accuracy on V_{cb} . Even if no longer usefull for V_{cb} measurements, the improved knowledge of the averaged B lifetime provides a baseline for the exclusive B lifetime measurements.

3.2.2 Experimental results

In these measurements, the selection has the same efficiency to keep all the four species of B hadrons (B_μ, B_d, B_s and Λ_b). Therefore the measured lifetime is the average /bB lifetime τ_b . Three classes of measurements are made :

- Impact parameters of leptons :

The observation of a high p and p_T lepton selects a B semileptonic decay with a high purity (see section 2.2.1). All four LEP experiments obtain results given in table 6a (none have been updated for this conference). This result is the only lifetime measurement obtained by L_3 which suffers of a worse tracking resolution. The table gives the data taking period, the measured quantity (spacial impact parameter, or projected on the transverse plane) and the achieved resolution on this quantity. All these results are statistically limited by the

modeling of the semileptonic decay. The LEP average of table 6a uses a common systematic error of 0.03 ps.

- B decays containing a J/ψ :

Events containing a J/ψ decay in a lepton pair are selected. The wide opening angle of the pair allows a good decay lenght resolution (190μ to 250μ). The B jet, built "around" the J/ψ (see section 3.1) gives the B momentum. The results of this method (table 6b), due to Delphi and Aleph and updated for this conference, show that while the statistics are limited, the systematical errors are small. With a similar technic and selection, CDF[26] has obtained : $\tau_B = 1.46 \pm 0.06 \pm 0.06$ ps.

- Inclusive B decays into hadrons :

Charged tracks measured in an event can be used to reveal the long lived B decays in an inclusive way. Results of four measurements of this kind are given in table 6c. In the first one (method A), Delphi uses topological vertices. This method has been greatly improved for this conference (method C): Secondary vertices are built, with at least 4 hadrons exceeding 1 GeV momentum. The invariant mass of this hadron system have to exceed 1.7 GeV and the transverse distance of the vertex to the beam to exceed 1 mm. With such cuts 8% of B are retained and the B purity is 93%. The decay lenght distribution is fitted to measure τ_B. In another method submitted to this conference (B), Delphi has studied the impact parameter distribution of high p and p_T hadrons, for events enriched in B in the other hemisphere (a 38% purity is achieved for an efficiency of 59%). This determination suffers of anisotropies in the tracking resolution which limit the systematical error. The last measurement (method D) has been developped by Aleph. The track topology in an event is examined to form, in the transverse plane, a pair of secondary vertices in opposite hemispheres. The transverse dipole separation is used to determine τ_B . This method is limited by a somewhat large systematical error.

All averaged B lifetime measurements from LEP give an average

$$\tau_B = 1.533 \pm 0.022 ps.$$

This value can be compared to the summer 93 LEP average of 1.489 ± 0.038 ps.

3.3 Individual B lifetimes

3.3.1 Theoretical motivations

The spectator model, useful to predict the averaged B lifetime, has proven to be very naïve in the charm sector where the individual charm hadron lifetimes have been measured to be very different, respectively 1.05, 0.47, 0.42 and 0.21 ps for the D^+, D^0, D_s and Λ_c. Non spectator effects, as illustrated in figure 3 for B decays, play an important role. Two spectator diagrams exist (fig. 3a and 3b) depending if the W radiation is external or internal to the incoming quark lines. The second diagram is colour suppressed. In the case of certain decay modes (for exemple $D^- \rightarrow \pi^- K^0$ or $\rho^- K^0$, $B \rightarrow \pi^- D^0$ or $\rho^- D^0$) both diagrams intervene and interfere destructively, leading to an increased lifetime. The third diagram of fig. 3c, the W-exchange diagram, occurs only in the decay of neutral mesons or of the baryon. It's contribution is helicity suppressed for the meson, but it leads for the baryon to a large decrease in the lifetime. The quantitative predictions derived from these considerations

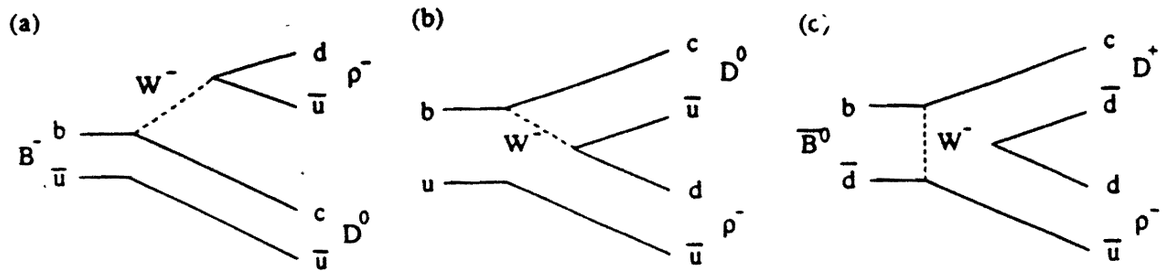

Figure 3: B hadron decay diagrams:

(a) Spectator decay, (b) "internal" spectator decay and (c) W-exchange.

Experiment	Ref.	Year of data	Method	τ_B (ps)
a) B $\longrightarrow$ lepton				
ALEPH	19	91	δ_2 (25μ)	1.49 $\pm$ 0.03 $\pm$ 0.06
ALEPH	20	92	δ_3 (25μ)	1.487 $\pm$ 0.023 $\pm$ 0.038
L3	21	90-91	δ_2 (110μ)	1.535 $\pm$ 0.035 $\pm$ 0.028
DELPHI	22	90	δ_2 (25μ)	1.37 $\pm$ 0.05 $\pm$ 0.05
OPAL	23	90-91	δ_2 (50μ)	1.523 $\pm$ 0.034 $\pm$ 0.038
LEP average				1.499 $\pm$ 0.035
b) B $\longrightarrow \psi\, x$				
ALEPH	24	91-93	L_3 (190μ)	1.43 $\pm$ 0.12 $\pm$ 0.0032
DELPHI	25	90-92	L_2 (250μ)	1.50 $^{+0.24}_{-0.21}$ $\pm$ 0.03
LEP average				1.45 $\pm$ 0.11
c) B $\longrightarrow$ hadrons				
DELPHI	27	91-92	A	1.59 $\pm$ 0.06 $\pm$ 0.09
DELPHI	28	91-92	B	1.542 $\pm$ 0.021 $\pm$ 0.045
		91-92	C	1.599 $\pm$ 0.014 $\pm$ 0.035
ALEPH	29	91	D	1.511 $\pm$ 0.022 $\pm$ 0.078
LEP Average				1.573 $\pm$ 0.030
LEP global average				1.533 $\pm$ 0.022

Table 6 : **Averaged B lifetime** measurements from LEP (ps), using, a) B $\rightarrow$ lepton events, b) B $\rightarrow \psi\, x$, $\psi \rightarrow 1^+1^-$ event and c) an inclusive selection of B $\rightarrow$ hadron events. The method label is explained in the text.

have been very successfull in describing the charm lifetime hierarchy. In the B sector, similar arguments apply but their size is reduced by mass effects. From charm to beauty, the hadron lifetime differences are expected to decrease like the inverse of the squared mass. Therefore the predicted hierarchy [10] is the following. Compared to the B_d^0 lifetime, the B_s^0 lifetime should not differ by more than 1%, the B_u^+ lifetime should be higher by $\sim$ 5% and the Λ_b lifetime smaller by $\sim$ 10%. Would this hierarchy be confirmed by experiments ? Are LEP experiments precise enough to observe so small differences ?

3.3.2 Averaging lifetime measurements

Averaging lifetime measurements deserves a special care. The collected number of events, for some measurements, can be as low as 20. The theoritical dependence of the likelihood function with the lifetime τ, when an exponential time distribution is fitted on data, is

$$\mathcal{L}_{th} = A \cdot [\ln(\tau/\tau_0) + \tau_0/\tau - 1].$$

$\mathcal{L}_{th}$ is minimum for $\tau = \tau_0$ and A is equal to the number of events, N. The quotted errors, where $\mathcal{L}_{th} = 0.5$, are then asymetrical, the asymetry depending on N. In real life the time measurement errors have to be added. They symetrise the error. Systematical errors have the same effect. The ideal solution, when averaging various measurements, is to add the likelihood function of each experiments. But what is published is only the most probable lifetime value τ_0 and the errors (statistical and sytematical). In order to estimate for each result the best likelihood dependence, we have adopted the following procedure. The positive and negative errors (statistical and sytematical) are added independently in quadrature to give σ_+ and σ_-. The likelihood shape is assumed to be

$$\mathcal{L} = \mathcal{L}_{th} + B(\tau/\tau_0 - 1)^2$$

where a symetrical term has been added to $\mathcal{L}_{th}$ given above. It is minimum for $\tau = \tau_0$ and A and B are determined such as $\mathcal{L} = 0.5$ for $\tau = \tau_0 - \sigma_-$ and $\tau = \tau_0 + \sigma_+$.

Then averaging various results consists in adding these functions, finding the minimum of the summed likelihood and the values where it exceeds this minimum by 0.5. This method has been used in the following when averaging individual lifetime measurements.

3.3.3 B_u^+ and B_d^0 lifetimes

B_u^+ and B_d^0 mesons are the most copious species produced in $b\bar{b}$ events. Their lifetime will therefore be measured with the best accuracy. The event selection must distinguish between them. Three methods are used, their result presented in table 7. None of the results have been updated for this conference.

- D (or D^*)-lepton correlations (method 1).

The proper time can be easily measured in such events (see section 3.1). The B semi-leptonic decay gives, most of the time, D (or D^*) $\ell\nu$. Apart from some confusion coming from the decay $D^{*-} \to \overline{D^0}\ \pi^-$ which can be corrected easily, the observation of a $\overline{D^0}$ (resp. a D^- or D^{*-}) signs the production of a B_u^+ (resp. a B_d^0). This ideal situation is somewhat worsened by the substential contribution (20 to 40%) of higher mass states (generically named D^{**}) in B semileptonic decays. The D^{**} decay in turn to D and D^* states reversing, part of the time, the charge tagging. This is evaluated and accounted for in the systematical

error. Aleph, Delphi and Opal have used this method (table 7). The data sample and the event selection vary from one experiment to the other. The quoted results are the two individual lifetimes $\tau_{B_u^+}$ and $\tau_{B_d^0}$ and their ratio.

• charge of topological vertices (method 2). This method from Delphi[33] follows somewhat the guidelines of method C of the previo us section. Secondary vertices are built and cleaned by cutting on their charge multiplicity (> 2), their invariant mass (> 2.2 GeV) and the allowed decay lenght resolution (< 600 μ). Delphi has shown that the total charge of a vertex keeps a good memory of the B charge. The fit to the decay lenght distributions, depending on this charge, allows a separate measurement of $\tau_{B_u^+}$ and $\tau_{B_d^0}$ and of their ratio (table 7).

• Fully reconstructed B (method 3). The best measurements of individual lifetimes come, from the point of view of systematical errors, from fully reconstructed decays. The first results of this type have been obtained by Aleph[34] and CDF[35]. Selected decay channels are as numerous as possible and involve the production of $D\ n\pi$ or $J/\psi\ K$ (only the latest for CDF). Statistics are limited (see table 7). The B charge and propertime are obviously known. Results are given in table 7.

An additional measurement of the lifetime ratio is provided at $\Upsilon(4s)$ machines by the determination of the ratio of the semi-leptonic branching ratio of B_u^+ and $B^0{}_d$ mesons (their semi-leptonic partial wi dths are assumed to be equal). The two B being produced coherently, the variety of the B decaying semi-leptonically is tagged from the opposite B. The CLEO result is given in table 7.

The results of table 7 average to :

$$\tau_{B_u^+} = 1.62 \pm 0.10 \ ps$$
$$\tau_{B_d^0} = 1.50 \pm 0.10 \ ps$$
$$\tau_{B_u^+}/\tau_{B_d^0} = 1.057 \pm 0.094$$

3.3.4 B_s^0 lifetime

The B_s^c being produced at LEP in only 12% of all B, the statistics are limited. Results are given in table 8. It is evident that methods 2 and 3 of the previous section cannot be used. Method 1 follows the same principles as before : $D_s^+\ell^-$ correlations are selected, D_s^+ being reconstructed in their $\phi\pi^+$ and $K^{*0}\ K^+$ decay modes. It has been applied by Aleph, Delphi and Opal with statistics between 19 and 31 B_s^0 events and also by CDF (41 events). Other methods have been developped relaxing the D_s-lepton correlation. This induces the following problem : the sample will be populated also by decays of other B than the B_s. The purity (ratio of B_s^0 over all B) of each method is given in table 8. It is above 90% for method 1 and ranges from 55% to 71% in these additional methods. Therefore the fit to the proper time distribution has to include a part for which the averaged B lifetime is fixed to the word value. These three alternative methods are method 2 (Delphi) which selects φ-lepton correlations and method 3 (Delphi) which uses only inclusive D_s (an additional background of $c\bar{c}$ events enters). They have been updated for this conference, using only 1991 data. More interesting and new at this conference is the Aleph result (method 4) where events containing a D_s ($\varphi\pi$ and K^*K) are seclected and the D_s vertexed with a fast charged

Exp.	Ref.	Year	Method	N_{B^+} N_{B^0}	$\tau_{B_u^+}$ (ps) $\tau_{B_d^0}$ (ps)	$\tau_{B_u^+}/\tau_{B_d^0}$
DELPHI	30	91	1	92 95	$1.30\ ^{+0.33}_{-0.29} \pm 0.16$ $1.17\ ^{+0.29}_{-0.33} \pm 0.16$	$1.11^{+0.51}_{-0.39} \pm 0.11$
ALEPH	31	91	1	77 77	$1.47\ ^{+0.22}_{-0.19}\ ^{+0.15}_{-0.14}$ $1.52\ ^{+0.20}_{-0.18}\ ^{+0.07}_{-0.13}$	$0.96\ ^{+0.19}_{-0.15}\ ^{+0.18}_{-0.12}$
OPAL	32	91-92	1	191 354	$1.66 \pm 0.20\ ^{+0.11}_{-0.12}$ $1.63 \pm 0.14\ ^{+0.10}_{-0.11}$	$1.02\ ^{+0.19}_{-0.17}\ ^{+0.08}_{-0.07}$
DELPHI	33	91-92	2	470 400	$1.81 \pm 0.12 \pm 0.19$ $1.37 \pm 0.15 \pm 0.21$	$1.32\ ^{+0.22}_{-0.18} \pm 0.21$
ALEPH	34	91-92	3	27 18	$1.77\ ^{+0.45}_{-0.34} \pm 0.14$ $1.19\ ^{+0.43}_{-0.29} \pm 0.14$	
LEP Average					1.637 ± 0.125 1.475 ± 0.115	$1.080\ ^{+0.138}_{-0.128}$
CDF	35		4	148 121	$1.61 \pm 0.16 \pm 0.05$ $1.57 \pm 0.18 \pm 0.08$	$1.02 \pm 0.16 \pm 0.05$
CLEO	36					$1.05 \pm 0.16 \pm 0.15$
Global average					1.625 ± 0.10 1.50 ± 0.10	1.057 ± 0.094

<u>Table 7</u> : $\mathbf{B_u^+}$, $\mathbf{B_d^0}$ **lifetime** measurements and their ratio from LEP, CDF and CLEO. The method label is explained in the text.

Experiment	Ref.	Year of data	Events	Purity %	Method	$\tau_{B_s^0}$ (ps)
ALEPH	37	91-92	31	93	1	$1.92\ ^{+0.45}_{-0.35} \pm 0.04$
OPAL	38	90-92	22	100	1	$1.13\ ^{+0.35}_{-0.26} \pm 0.09$
DELPHI	39	91-92	19	90	1	$1.29 \pm 0.42 \pm 0.20$
DELPHI	40	91	31	66	2	1.08 ± 0.73
DELPHI	40	91	19	71	3	$0.75\ ^{+0.49}_{-0.33} \pm 0.22$
ALEPH	41	91-93	319	55	4	$1.75\ ^{+0.32}_{-0.30}\ ^{+0.14}_{-0.20}$
LEP average						$1.48\ ^{+0.17}_{-0.16}$
CDF	42		41	high	1	$1.54\ ^{+0.42}_{-0.34}\ ^{+0.11}_{-0.12}$
Global average						$1.495\ ^{+0.154}_{-0.149}$

Table 8 : **B_s^0 lifetime** measurement from LEP and CDF. The purity is the ratio of B_s^0 over all B mesons contained in the selected sample. The method label is explained in the text.

track. 319 events are found, the purity is 55%. Nevertheless the accuracy achieved by this method is comparable to others.

The results of table 8 average to

$$\tau_{B_s} = 1.49 \pm 0.15\ ps$$

3.3.5 Λ_b lifetime

As for the B_s, the production rate is low. Method 1, as before, searches for $\Lambda_c - \ell$ correlations with the Λ_c fully reconstructed. Only one decay mode ($p\ K\ \pi$) has been observed. Delphi and Aleph have given results (table 9). The baryon's case offers the possibility to look for other types of correlations with leptons, keeping the advantage that the fake correlation rate is monitored from the wrong sign sample. Method 2 and 3 look for $\Lambda - \ell$ correlations. A difficulty occurs, Λ being very long-lived, they are useless to find the Λ_b vertex, so to measure the decay lenght. To overcome this difficulty, three methods have been used. • The Λ_b lifetime is derived from a fit to the lepton impact parameter distribution (method 2, Aleph). • The Λ_b decay lenght is computed, event by event, either by assuming the Λ_b direction to be the direction of the jet containing the lepton and the Λ (method 2, Opal) or by vertexing the lepton with a fast hadron of the event (method 3, Delphi). At last, method 4 is a new method presented at this conference. Using the nice particle identification capabilities of the gas RICH detector, Delphi selects very clean p-μ correlations (47 events) coming from a Λ_b decay. The data corresponds to half a million Z decay.

The average of the results of table 9 is :

$$\tau_{\Lambda_b} = 1.10 \pm 0.14\ \ ps$$

Experiment	Ref	Year of data	Events	Method	τ_{Λ_b} (ps)
DELPHI	43	90-92	12	1	$1.40\ ^{+2.10}_{-0.60} \pm 0.30$
ALEPH	44	90-93	31	1	$1.06\ ^{+0.40}_{-0.27} \pm 0.06$
ALEPH	45	90-91	122	2	$1.12\ ^{+0.32}_{-0.29} \pm 0.16$
OPAL	46	90-92	157	2	$1.05\ ^{+0.23}_{-0.20} \pm 0.08$
DELPHI	47	90-92	20	3	$1.05\ ^{+0.38}_{-0.29} \pm 0.20$
DELPHI	48	92 (*Rich*)	47	4	$1.21\ ^{+0.35}_{-0.29} \pm 0.15$
LEP average					1.10 ± 0.14

Table 9 : Λ_b **baryon lifetime** measurements from LEP. The method label in explained in the text.

3.4 Lifetimes summary and prospects

All the lifetimes averages presented before are summarized in table 10. The individual lifetimes are compared by computing the shift (in %) of each lifetime to the B_d^0 lifetime. The observed hierarchy follows the theoretical expectations with a little reserve for the Λ_b whose shift is rather large. The relative errors are of 1.4% on the averaged B lifetime, 7.5% on the B_u^+ and B_d^0 lifetime and 12.5% on the B_s^0 and Λ_b. They correspond to about 1.7 million hadronic Z decays accumulated per experiment. In the prospect of the LEP100 end of running, 3 to 5 millions Z may be accumulated allowing the above errors to be scaled down by a factor 0.5 to 0.6.

B hadron	τ (ps) LEP + CDF	$(\tau/\tau_{B_d^0} - 1) \times 100$	
		Measured	**Theory**
All hadrons averaged	1.533 ± 0.022		
B_u^+	1.62 ± 0.10	$8. \pm 10.\%$	5%
B_d^0	1.50 ± 0.10	0	0
B_s^0	1.49 ± 0.15	$-1. \pm 12\%$	$\leq 1\%$
Λ_b	1.10 ± 0.14	$-27. \pm 11\%$	-10%

Table 10 : Summary of all B hadrons measurement. The lifetime hierarchy (with respect to the B_d^0 lifetime) is compared to the theoretical expectation [18].

4 Conclusions

We have presented mixing and lifetime results obtained at LEP and averaged them including a few results coming from other colliders.

On mixing, where time integrated and time dependent measurements are performed, the following results have been obtained.

- B_d^0, B_s^0 average : $\chi = 0.1241 \pm 0.0068$
- B_d^0 : $\chi_d = 0.175 \pm 0.018$ or $\Delta m_d = 3.16 \pm 0.25 \cdot 10^{-4}\mathrm{eV}/c^2$
- B_s^0 : $\chi_s > 0.43$ or $\Delta m_s > 12. \cdot 10^{-4}\mathrm{eV}/c^2$ (95% C.L.).

This permits to derive a model independant determination of the fraction of B_s produced in the hadronisation of a b quark of

$$f_s = 0.113 \, ^{+0.027}_{-0.026} \, .$$

On lifetime the following averages are obtained :

Averaged B	:	1.533	$\pm$	0.022 ps
B_u^+	:	1.62	$\pm$	0.10 ps
B_d^0	:	1.50	$\pm$	0.10 ps
B_s^0	:	1.49	$\pm$	0.15 ps
Λ_b	:	1.10	$\pm$	0.14 ps

This lifetime hierarchy follows the theoretical expectation except for some reserve for the somewhat low value of the Λ_b lifetime.

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