MEASUREMENT OF THE LIFETIME RATIO $\tau(B^+)/\tau(B^0)$

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Using the ARGUS detector at the e^+e^- storage ring DORIS II the ratio of semileptonic branching ratios of B^+ and B^0 mesons has been determined by comparing the yields of $\bar{D}^0$, D^-, and $D^*(2010)^-$ mesons in semileptonic B decays. We derive the lifetime ratio $\tau(B^+)/\tau(B^0) = 1.00 \pm 0.23 \pm 0.14$.

The lifetimes of B_u^+ and B_d^0 mesons have not yet been measured separately. Decay-in-flight measurements of the b hadron lifetime at PEP and PETRA [1] only yield the average over an unknown mixture of b-flavoured hadrons. However, the lifetime ratio $\tau(B^+)/\tau(B^0)$ is important for understanding the decay mechanisms of B mesons. A pure spectator model predicts equal B^+ and B^0 lifetimes. Measurements of lifetime differences thus provide information on the role of non-spectator processes in weak hadronic decays. In the case of the charmed mesons D^+ and D^0, the ratio of lifetimes has been measured to be 2.6 ± 0.1 [2]. This can be qualitatively explained by taking into account annihilation diagrams and quark interference [3–6]. In B decays these effects are assumed to be smaller; for higher quark masses one expects a better agreement with the spectator model. Hence, the lifetime ratio should be close to one [7,8], although some models predict higher values [9]. Furthermore, the B^+ and B^0 lifetimes enter into every evaluation of decay widths from measured branching ratios and thereby also into the determination of the Kobayashi–Maskawa matrix element V_{cb} from exclusive semileptonic decays [10–12]. Currently, one has to assume the lifetimes to be equal. It is valuable to justify this experimentally. Until now, only weak bounds have been obtained from the single lepton and dilepton rate in $\Upsilon(4S)$ decays: $0.43 < \tau(B^+)/\tau(B^0) < 2.3$ at 90% CL [13].

The ratio of the B^+ and B^0 lifetimes can be extracted from a reconstruction of semileptonic B decays with a $\bar{D}^0$, D^- or D^{*-} meson detected in the final state [#1]. Due to the absence of final state interactions, the partial widths of semileptonic B^+ and B^0 decays can be assumed to be equal. This is true in the case of D mesons [14]. Explicitly, $\Gamma(B^+ \to \bar{D}^0 \ell^+ \nu) = \Gamma(B^0 \to D^- \ell^+ \nu)$ and $\Gamma(B^+ \to \bar{D}^{*0} \ell^+ \nu) = \Gamma(B^0 \to D^{*-} \ell^+ \nu)$ implies

$$\frac{\tau(B^+)}{\tau(B^0)} = \frac{BR(B^+ \to \bar{D}^0 \ell^+ \nu) + BR(B^+ \to \bar{D}^{*0} \ell^+ \nu)}{BR(B^0 \to D^- \ell^+ \nu) + BR(B^0 \to D^{*-} \ell^+ \nu)}, \quad (1)$$

where ℓ denotes a lepton e or μ.

These decays into the lowest-lying charmed pseudoscalar and vector mesons are expected to dominate the total semileptonic decay rate [7,15]. This has been confirmed by recent measurements [10–12], where the production of excited charmed states in semileptonic decays is found to be small. It is therefore neglected here but will be discussed below. Since $\bar{D}^{*0}$ decays do not produce D^- mesons [16], all D^- mesons in semileptonic decays originate from B^0 decays, while semileptonic B^+ decays always yield $\bar{D}^0$ mesons. Thus the charge of the final state D meson serves as a tag for the charge of the B, except for $\bar{D}^0$ mesons produced in the chain $B^0 \to D^{*-} \ell^+ \nu$, $D^{*-} \to \bar{D}^0 \pi^-$. This decay has, however, been exclusively measured [17,11]. Taking this into account, one has

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$$\frac{f_+}{f_0}\frac{\tau(\mathrm{B}^+)}{\tau(\mathrm{B}^0)} = \frac{N(\bar{\mathrm{D}}^0\ell^+) - r^* N(\mathrm{D}^{*-}\ell^+, \mathrm{D}^{*-}\to\bar{\mathrm{D}}^0\pi^-)}{r^- N(\mathrm{D}^-\ell^+) + r^* N(\mathrm{D}^{*-}\ell^+, \mathrm{D}^{*-}\to\bar{\mathrm{D}}^0\pi^-)} . \quad (2)$$

where $N(\bar{\mathrm{D}}^0\ell^+)$ $[N(\mathrm{D}^-\ell^+)]$ denotes the observed number of $\bar{\mathrm{D}}^0$ $[\mathrm{D}^-]$ lepton pairs and $N(\mathrm{D}^{*-}\ell^+, \mathrm{D}^{*-}\to\bar{\mathrm{D}}^0\pi^-)$ the number of those D^{*-}–lepton combinations, where the D^{*-} has been reconstructed in the decay channel $\mathrm{D}^{*-}\to\bar{\mathrm{D}}^0\pi^-$. The coefficients r^* and r^- account for the reconstruction efficiencies of $\bar{\mathrm{D}}^0$ decays relative to D^{*-} and D^- decays, respectively. The abundances of charged and neutral B mesons are given by f_+ and f_0. It should be noted that expression (2) does not contain D^{*-} branching ratios nor the relative strength of the decays into pseudoscalar and vector particles. The ratio of their sums is measured, and therefore lepton detection and model dependent momentum cut efficiencies cancel exactly.

The data sample used for this analysis corresponds to an integrated luminosity of 172 pb^{-1} taken on the $\Upsilon(4S)$ resonance with the ARGUS detector at the e^+e^- storage ring DORIS II. It contains about 150000 B meson pairs. The ratio $f_+/f_0 = \mathrm{BR}(\Upsilon(4S)\to \mathrm{B}^+\mathrm{B}^-)/\mathrm{BR}(\Upsilon(4S)\to\mathrm{B}^0\bar{\mathrm{B}}^0)$ is not known. We use $f_+ = f_0$, which is suggested by recent measurements of the B^+ and B^0 masses [18] and also favoured by theoretical models of quarkonium decays [19].

The ARGUS detector, its trigger requirements and particle identification capabilities have been described in detail [20]. The techniques applied for identifying leptons are the same as in the exclusive studies [10,12,17]. D mesons are reconstructed in the channels

$$\bar{\mathrm{D}}^0\to\mathrm{K}^+\pi^- , \quad (3)$$

$$\mathrm{D}^-\to\mathrm{K}^+\pi^-\pi^- , \quad (4)$$

$$\mathrm{D}^{*-}\to\bar{\mathrm{D}}^0\pi^-, \quad \bar{\mathrm{D}}^0\to\mathrm{K}^+\pi^- . \quad (5)$$

The $\bar{\mathrm{D}}^0$ candidate in the chain (5) is kinematically fitted to its nominal mass [21]. We accept only those $\mathrm{K}\pi(\pi)$ combinations which satisfy $\cos\theta^*_{\mathrm{K}} < 0.8$. Here we define θ^*_{K} as the angle between the K^+ flight direction and the $\bar{\mathrm{D}}$ boost direction, as measured in the rest frame of the $\bar{\mathrm{D}}$. The $\cos\theta^*_{\mathrm{K}}$ distribution arising from decays of the pseudoscalar $\bar{\mathrm{D}}$ mesons should be isotropic, while the background from random $\mathrm{K}\pi(\pi)$ combinations peaks towards $\cos\theta^*_{\mathrm{K}} = 1$.

Background $\bar{\mathrm{D}}\ell^+$ combinations can arise from the continuum underneath the $\Upsilon(4S)$ resonance and from the $\Upsilon(4S)$ itself. In order to suppress events from the continuum reaction $e^+e^-\to c\bar{c}\to \mathrm{D}\bar{\mathrm{D}}\mathrm{X}$, followed by a semileptonic D decay, we require the scaled momentum of the $\bar{\mathrm{D}}$ candidate, $x_0 \equiv p_{\mathrm{D}}/p_{\mathrm{max}}$, to be less than 0.5, where $p^2_{\mathrm{max}} = E^2_{\mathrm{beam}} - m^2_{\mathrm{D}}$. This condition is necessarily fulfilled for B meson decay products.

In $\Upsilon(4S)$ decays background from uncorrelated $\bar{\mathrm{D}}\ell^+$ pairs is predominantly due to the cascade decay $\bar{\mathrm{B}}\to\mathrm{DX}$, $\mathrm{D}\to\ell^+\mathrm{X}'$. These secondary leptons exhibit a softer momentum spectrum than primary leptons from a semileptonic B decay. We therefore require that the lepton momentum be greater than 1.2 GeV/c.

In order to further suppress this background as well as the contribution from mixed events $\Upsilon(4S)\to\mathrm{B}^0\bar{\mathrm{B}}^0$ followed by $\mathrm{B}^0\to\bar{\mathrm{D}}\mathrm{X}$ and $\bar{\mathrm{B}}^0\to\mathrm{B}^0\to\ell^+\mathrm{X}'$, we calculate for each combination the recoil mass squared against the D–lepton system,

$$M^2_{\mathrm{R}} = [E_{\mathrm{B}} - (E_{\mathrm{D}} + E_{\ell})]^2 - [\boldsymbol{p}_{\mathrm{B}} - (\boldsymbol{p}_{\mathrm{D}} + \boldsymbol{p}_{\ell})]^2 . \quad (6)$$

For B mesons produced on the $\Upsilon(4S)$ resonance the energy of the B meson is given by the well-measured beam energy, and its momentum can be neglected.

The spectra of the recoil mass squared for $\bar{\mathrm{D}}^0\ell^+$, $\mathrm{D}^-\ell^+$, and $\mathrm{D}^{*-}\ell^+$ combinations are shown in fig. 1. They are obtained by dividing the events into bins of M^2_{R}. The number of events in each bin is then determined by a fit to the invariant mass distributions of $\mathrm{K}^+\pi^-$, $\mathrm{K}^+\pi^-\pi^-$, and $\bar{\mathrm{D}}^0\pi^-$ combinations, respectively, where we use the same parametrizations for signal and background shapes as in our study of inclusive D meson production [22]. One observes prominent peaks near $M^2_{\mathrm{R}} = 0$ due to decays $\mathrm{B}\to\bar{\mathrm{D}}^{(*)}\ell^+\mathrm{X}$, above low background. The M^2_{R} behaviour thus provides a clear signature for semileptonic decays even in the semi-exclusive case. Compared to the $\mathrm{D}^{*-}\ell^+$ distribution, the $\bar{\mathrm{D}}^0\ell^+$ and $\mathrm{D}^-\ell^+$ signals are broader and shifted towards positive values of M^2_{R}. This reflects the dominance of the decay modes $\mathrm{B}\to\bar{\mathrm{D}}^*\ell^+\nu$, where the recoil mass against the $\bar{\mathrm{D}}\ell^+$ system is the invariant mass of the system formed by the neutrino and the pion or photon pro-

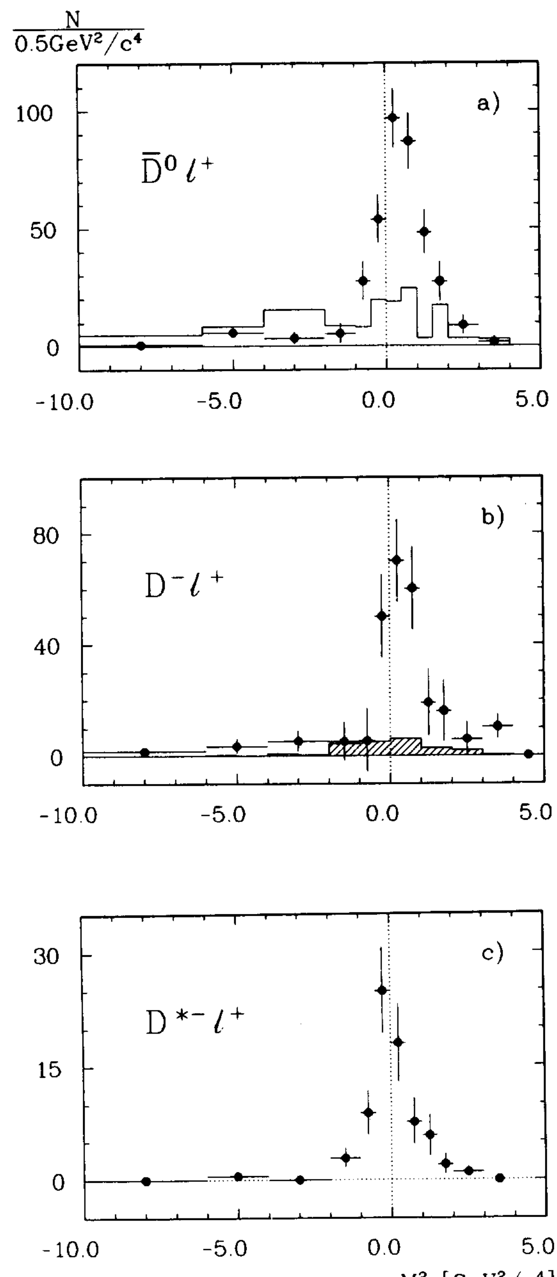


Fig. 1. M_R^2 distributions, obtained by fits to invariant mass spectra in each bin, for (a) $\bar{D}^0\ell^+$ combinations (full dots) and $\bar{D}^0\ell^-$ combinations (histogram); (b) $D^-\ell^+$ combinations (full dots); and (c) $D^{*-}\ell^+$ combinations, with $x_p(\bar{D}^0, D^{(*)-})<0.5$ and $p_\ell > 1.2$ GeV/c. The hatched histogram in (b) is the continuum background contribution.

duced along with the $\bar{D}$ meson in the $\bar{D}^*$ decay. In fig. 1a we also show the M_R^2 spectrum of $\bar{D}^0\ell^-$ combinations, which have the same kinematical properties as the background from mixed events. The background due to secondary leptons has almost the same shape. The distribution extends towards large negative values, while the recoil mass squared of $\bar{D}\ell^+$ combinations from semileptonic decays has to be consistent with 0 or a positive value. Hence, we further require $M_R^2 > -1$ GeV $^2/c^4$.

The numbers of $\bar{D}^0\ell^+$, $D^-\ell^+$ and $D^{*-}\ell^+$ combinations fulfilling these cuts are listed in table 1. The invariant mass spectra of all accepted $K^+\pi^-$, $K^+\pi^-\pi^-$ and $\bar{D}^0\pi^-$ combinations accompanied by leptons are shown in fig. 2, together with the curves representing the results of the fits.

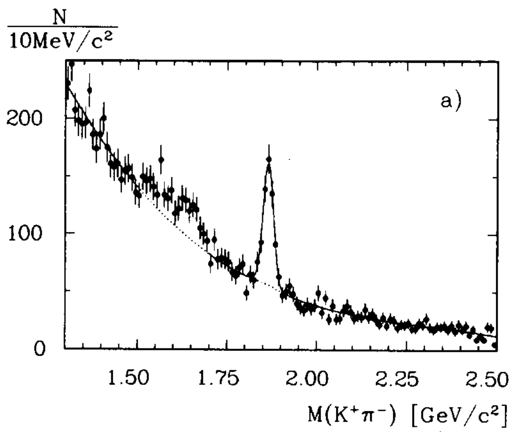
The remaining background from the sources mentioned above and that due to fake leptons is determined using the technique described in refs. [10,24]. The result is summarized in table 1. The continuum contribution is the dominant source of background. Its M_R^2 shape has been obtained by Monte Carlo studies, while its normalization can be determined from the data. In the $D^{*-}\ell^+$ case, we simply scale the number of events measured in the continuum just below the $\Upsilon(4S)$ resonance by the ratio of luminosities. For D mesons, however, this method suffers from a poor signal-to-background ratio at low D momenta. Therefore, we employ a different technique, using the x_p spectra shown in fig. 3, which result from fitting the $K^+\pi^-$ and $K^+\pi^-\pi^-$ invariant mass distributions in bins of x_p. For this purpose only the lepton momentum cut $p_\ell > 1.2$ GeV/c was applied. Fragmentation functions according to the Lund Monte Carlo [25] are fitted to the data points with $x_p > 0.5$ (curves in fig. 3). The shape parameters have been determined in the inclusive study of D meson production [22]. Extrapolation towards zero momentum provides the normalization in the whole M_R^2 range. We show this background as a hatched histogram in fig. 1b.

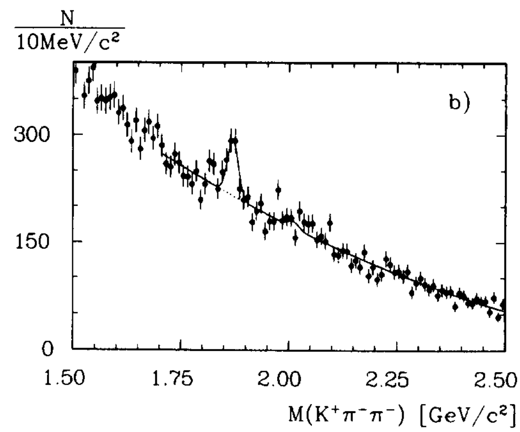
After background subtraction, we obtain $325\pm28\pm9$, $183\pm37\pm12$ and $58\pm9\pm3$ events from the decays $B\to\bar{D}^0\ell^+X$, $B\to D^-\ell^+X$ and $B\to D^{*-}\ell^+X$ respectively (table 1). In order to calculate the lifetime ratio from (2), the coefficients r^* and r^- were determined from Monte Carlo generated events. The first is $r^* = 1/\eta(\pi_s)$, where $\eta(\pi_s)$ is the momentum

Table 1
Event and background summary for the $\bar{D}^0\ell^+$, $D^-\ell^+$ and $D^{*-}\ell^+$ combinations. The first errors represent the statistical and the second the systematical uncertainty. The total number of events and the continuum background are obtained as described in the text. The contributions from uncorrelated $\bar{D}\ell^+$ pairs can be calculated from the mixing parameter χ [23] and measured branching ratios [21]; the acceptances are obtained by Monte Carlo simulations. The fake lepton background is determined from the data by using $\bar{D}$ hadron combinations and a hadron–electron (muon) misidentification probability of 0.5 (2%).

	$\bar{D}^0\ell^+$			$D^-\ell^+$			$D^{*-}\ell^+$		
total number of events	372.5	±27.3	±6	243.0	±36.2	±6	66.1	±9.2	±3
background: continuum	25.6	±4.6	±5.7	33.7	±6.6	±7.6	2.6	±1.7	
mixed events	5.9		±2.7	10.0		±4.6	2.9		±1.3
secondary leptons	5.8		±2.8	5.0		±2.6	1.1		±0.6
fake leptons	10.5	±1.5	±2.7	11.2	±2.3	±2.2	1.4		±0.3
events from decays $B\to\bar{D}\ell^+X$	324.7	±27.7	±9.5	183.1	±36.9	±11.2	58.1	±9.4	±3.3

dependent reconstruction efficiency of the slow daughter pion in the D^{*-} decay. Using the D^{*-} momentum spectrum of the BSW model [3,26], which is in good agreement with our earlier measurements [10], we obtain $\eta(\pi_s)=(53\pm4)\%$. The reconstruction efficiencies for the $\bar{D}^0$ and D^- decays are independent of the momentum; their ratio is $\eta(\bar{D}^0)/\eta(D^-)=1.25\pm0.06$. Using the MARK III branching





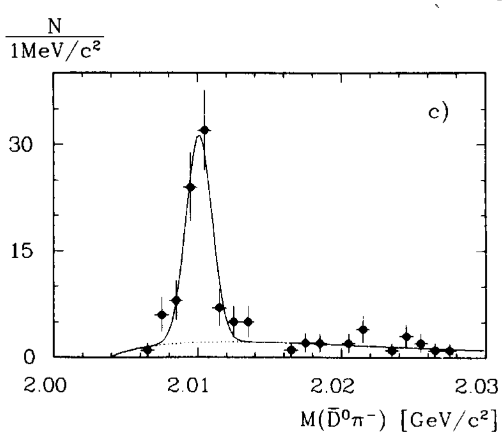


Fig. 2. Invariant mass spectra for (a) $K^+\pi^-$, (b) $K^+\pi^-\pi^-$ and (c) $\bar{D}^0\pi^-$ combinations with $x_p<0.5$, forming together with a lepton with $p_\ell>1.2$ GeV/c a system with recoil mass squared $M_R^2>-1$ GeV$^2/c^4$. Each solid line represents the result of a global fit of a gaussian for the signal plus a background function. The latter is shown as a dotted line separately.

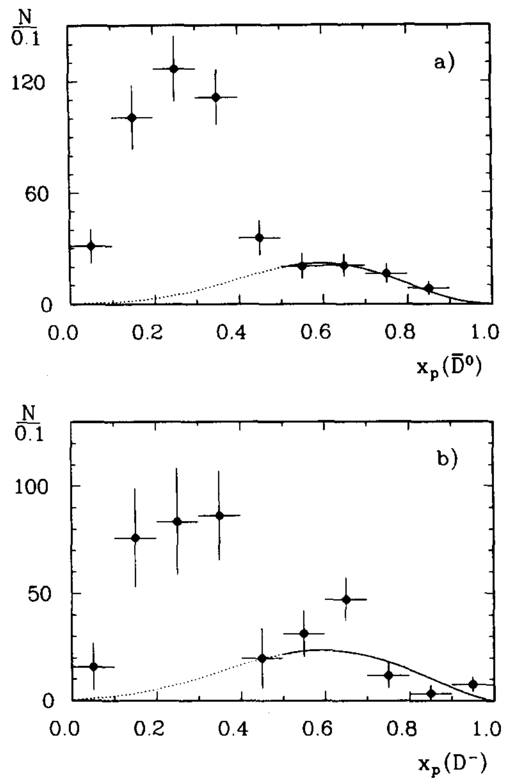


Fig. 3. x_p spectra for (a) $\bar{D}^0$ and (b) D^- mesons in events containing a lepton with $p_\ell > 1.2$ GeV/c. The solid lines are fragmentation functions, fitted to the points with $x_p > 0.5$ in order to normalize the continuum background by extrapolation towards zero momentum (dotted line).

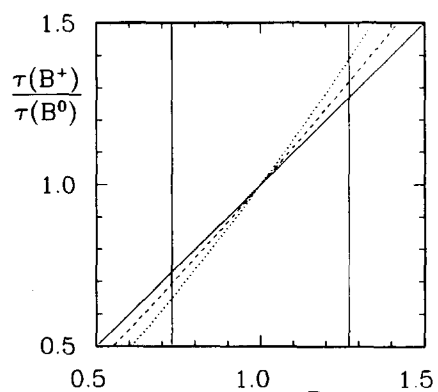


Fig. 4. The lifetime ratio $\tau(B^+)/\tau(B^0)$ as a function of the measured ratio R (right-hand side of eq. (2)), for $f_+ = f_0$ and various contributions δ from decays $B \to \bar{D}_J^* \ell^+ \nu$. Solid line: $\delta = 0$, dashed: $\delta = 0.1$, dotted: $\delta = 0.2$. The vertical lines represent the $\pm 1\sigma$ bounds of our measurement.

ratios $BR(D^0 \to K^- \pi^+) = (4.2 \pm 0.4)\%$ and $BR(D^+ \to K^- \pi^+ \pi^+) = (9.1 \pm 1.3)\%$ [27], we get $r^- = 0.58 \pm 0.10$. Inserting these numbers into (2), we obtain

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.00 \pm 0.23 \pm 0.14. \quad (7)$$

The contributions to the statistical error from $N(\bar{D}^0 \ell^+)$, $N(D^- \ell^+)$ and $N(D^{*-} \ell^+)$ are 13%, 10% and 16% respectively. The uncertainty in the D^0 and D^+ branching ratios represents the largest contribution (9%) to the systematic error; the remaining contributions arise from efficiency and background calculations.

Finally, we discuss how our result would be affected by decays $B \to \bar{D}_J^* \ell^+ \nu$, where $\bar{D}_J^*$ denotes any excited charmed meson state. Such decays have not yet been observed, but can be excluded to occur at a level of more than about 20% of the inclusive semileptonic rate [10–12]. The GISW model [28] predicts a relative contribution $\delta \equiv \Gamma(B \to \bar{D}_J^* \ell^+ \nu) / \Gamma(\bar{b} \to \bar{c} \ell^+ \nu) \approx 10\%$. Assuming isospin conservation in the decays of the $\bar{D}_J^*$ mesons into the lower-lying $\bar{D}$ and $\bar{D}^*$ states, this can be taken explicitly into account. It should be noted that the ratio of D and $D^*(2010)$ mesons produced in these decays does not enter into the calculation. Denoting by R the right-hand side of eq. (2), one finds

$$\frac{f_+}{f_0} \frac{\tau(B^+)}{\tau(B^0)} = \frac{R - \frac{2}{3}\delta(R+1)}{1 - \frac{2}{3}\delta(R+1)}. \quad (8)$$

In fig. 4 we show $\tau(B^+)/\tau(B^0)$ as a function of R for $f_+ = f_0$ and various values of δ. For $\delta < 20\%$ and $0.77 < R < 1.33$, the lifetime ratio differs from R by less than 10%, thought the error is slightly increased, as can be inferred from the figure.

In summary, we have determined the ratio of the B^+ and B^0 lifetimes to be $1.00 \pm 0.23 \pm 0.14$, where equal production of B^+B^- and $B^0\bar{B}^0$ pairs in $\Upsilon(4S)$ decays has been assumed. The agreement of the B meson lifetime ratio with the prediction from a pure quark spectator model is therefore much better than in the D meson case.

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