DETERMINATION OF THE AVERAGE LIFETIME OF BOTTOM HADRONS

TASSO Collaboration

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For footnotes see next page.

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We have determined the average lifetime of hadrons containing b quarks produced in e^+e^- annihilation to be

$$\tau_B = \left(1.83 \begin{smallmatrix} +0.38 & +0.37 \\ -0.37 & -0.34 \end{smallmatrix}\right) \times 10^{-12} \mathrm{s}.$$

Our method uses charged decay products from both non-leptonic and semileptonic decay modes.

In recent years the lifetimes of charmed hadrons have been measured using several different techniques and a consistent picture is beginning to emerge. The corresponding field for bottom hadrons (B), on the other hand, is still in its infancy. Three groups have reported on B-lifetime measurements [1–3]. They have measured the impact parameter distribution of leptons in hadronic events produced by e^+e^- annihilation. The contribution from semileptonic B decays has been extracted by selecting on the transverse momentum of the lepton and in this way the B lifetime averaged over the semileptonic decays of the B hadrons has been determined. We present in this paper a measurement of the B lifetime obtained from impact parameter distributions of charged tracks from all decay modes. This is achieved by employing a method rather different from that normally used. This method will be motivated by an approximate calculation to show the size of the observable effect for a nonzero B lifetime.

The experiment was performed with the TASSO detector at the DESY e^+e^- storage ring PETRA at CM energies W between 30 and 46.8 GeV. The data were taken with two different configurations of the central detector.

In the earlier configuration [4,5] the beam pipe (inner radius 12.4 cm) was followed by the proportional chamber and drift chamber (which has 9 zero-degree and 6 stereo layers with innermost and outermost radii of 36.7 and 122.2 cm). The track properties relevant to this measurement were determined with the drift chamber and proportional chamber. The position resolution of the drift chamber in the plane perpendicular to the beams ($r\varphi$ plane) is $\sigma_{r\varphi} \approx 250\ \mu$m averaged over a drift cell. The material between the interaction point and the drift chamber amounted to 13% of a radiation length (r.l.), the major part being concentrated at or near the beam pipe. The momentum resolution including multiple scattering was $\sigma_p/p = 0.16(1+p^2)^{1/2}$, p in GeV/c. With this configuration a total luminosity of 78.7 pb^{-1} was collected at W = 30–36.7 GeV, the average energy being $\bar{W}$ = 34.6 GeV.

In the current configuration the original beam pipe has been removed and a high precision drift chamber, the vertex detector, installed [6]. The vertex detector is mounted on a beryllium beam pipe of 6.5 cm radius which serves as its inner wall. The vertex detector has 8 zero-degree layers with innermost and outermost radii of 8.1 and 14.9 cm. The position resolution was $\sigma_{r\varphi} = 90\ \mu$m for isolated tracks and 100 μm averaged over the tracks in hadronic events. The material between the interaction point and the first layer of the vertex detector amounts to 0.7% r.l., and to 8.5% r.l. between the interaction point and the first layer of the outer drift chamber. The combination of vertex detector and drift chamber leads to a momentum resolution of $\sigma_p/p = 0.0095(0.5+p^2)^{1/2}$. A total luminosity of 13.7 pb^{-1} was collected in this configuration at W = 39.8–46.8 GeV, the average energy being $\bar{W}$ = 43.3 GeV.

The $e^+e^- \to$ multihadron events were detected in the central detector using the information on charged particles. In both cases the data taking, analysis procedure and event selection have been described in ref. [7]. A total of 22 474 events was accepted at $\bar{W}$ = 34.6 GeV and 2001 events with useful vertex detector infor-

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mation were accepted at 43.3 GeV. In order to ensure an accurate measurement on the B-direction of flight, only events for which $|\cos\theta_{jet}| < 0.7$ were used, where θ_{jet} is the angle between the sphericity axis and the beam direction. Furthermore, only events from running periods where the position of the e^+e^- interaction point was well determined were accepted. These conditions were satisfied by 17 103 events at 34.6 GeV and 1454 events at 43.3 GeV.

To reduce the contributions to the impact parameter distribution (see fig. 1a) from K^0 and Λ decays and from multiple scattering, in addition to the standard cuts [7] the tracks had to satisfy the following requirements:

(a) $|z| < 2(3)$ cm at 34.6(43.3) GeV, where z is the track coordinate at the point of closest approach to the beam measured in the z direction.

(b) $\chi^2_{r\varphi} < 2(5)$ at 34.6(43.3) GeV, $\chi^2_z < 2$, where $\chi^2_{r\varphi}$ and χ^2_z measure the chi-square values per degree of freedom for the $r\varphi$ and rz track fits.

(c) For the 43.3 GeV data each accepted track had to have at least 5 associated hits in the vertex detector.

(d) Momentum $p > 1$ GeV/c.

A total of 51 340 and 4884 tracks at 34.6 and 43.3 GeV, respectively, passed these cuts.

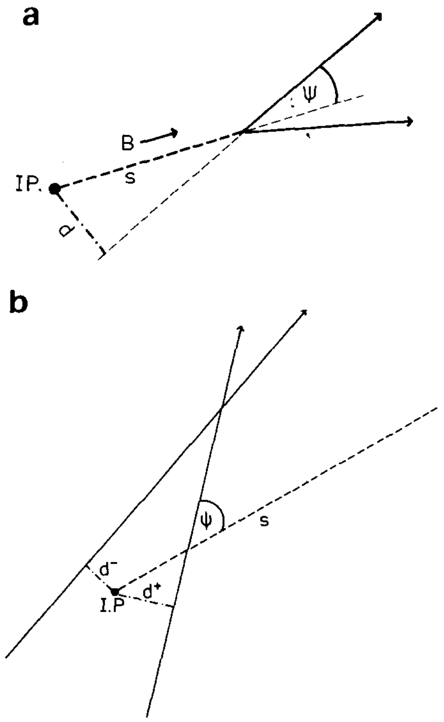

Fig. 1. (a) Definition of quantities used in the analysis of B decays. The B meson travels a distance, assumed to be s, along the sphericity axis (dashed line), from the interaction point (IP) before decaying to give a track whose angle with respect to the B line of flight is ψ. The impact parameter is given by the distance d, and is positive. (b) Two tracks, which because of reconstruction errors or multiple scattering do not point at the interaction point. The signed impact parameter is positive (d^+) in one case and negative (d^-) in the other.

Method of lifetime determination. The B lifetime was determined by measuring the reconstructed distance of closest approach to the interaction point or impact parameter [1] distribution of *all* charged particles rather than considering only that of leptons. In order to illustrate the essential features of our method we give an approximate calculation of the effect of the B lifetime on the impact parameter distribution. The definition of the impact parameter d is illustrated in fig. 1a. It is the distance of closest approach between a track and the interaction point. The B direction of flight was assumed to be given by the sphericity axis. It was checked that using thrust rather than sphericity has a negligible effect on the d distribution. The sign of d was defined as follows: it was positive if the track made an angle $\psi < 90°$ ($\psi > 90°$) with the B direction *and* crossed the B flight path after (before) the interaction point. In all other cases the sign of d was taken to be negative, for example see fig. 1b. The decay length of a B particle can be expressed in terms of the impact parameter of a decay track forming an angle ψ with respect to the B direction of flight (assuming the tracks to be straight):

$$s = d/\sin\psi\,, \tag{1}$$

which yields for the lifetime of this B particle

$$\tau_B = (1/\gamma\beta c)\, d/\sin\psi\,, \tag{2}$$

where βc and $\gamma = E_B/M_B$ are the velocity and Lorentz factor of the B. For zero mass decay products and a relativistic B, the angle ψ is related to its corresponding value in the B rest system, ψ^*, by

$$\langle\sin\psi\rangle \approx \gamma^{-1}\langle\tan\psi^*/2\rangle\,, \tag{3}$$

where $\langle\ \rangle$ indicates the average over the decay angular distribution. For isotropic decays

$$\tau_B \approx c^{-1}(2/\pi)\langle d\rangle\,. \tag{4}$$

Note that under the approximations made the average impact parameter is independent of the B momentum. We shall determine δ, the projection of the impact parameter in the $r\varphi$ plane, where the measuring accuracy is best. The average over the B direction of flight yields

$$\tau_B = f c^{-1} \langle \delta \rangle \,, \tag{5}$$

where the factor f depends on δ, the kinematics of B decay, the B production angular distribution and the acceptance of the detector. For the present analysis f is approximately 2.0 and has about the same value for both B and C decay independent of the B enrichment procedure described below, where C denotes charmed hadrons.

It is important to notice that each of the decay products from a B decay has an average impact parameter value given by eq. (5). Since the mean charged multiplicity in the decay of B mesons is [8] 5.75 ± 0.20 ± 0.10, the B-impact parameter enters for an average $b\bar{b}$ event $N_b = 11.5$ times. In contrast, charmed meson decay with a mean charged multiplicity for D^0, $D^{\pm}$ decay of [9] 2.3 ± 0.15 ± 0.11 yields an average of $N_c = 4.6$ entries for $c\bar{c}$ events. As a result, including all charged particles from B decay in the impact parameter distribution instead of using only the leptons enhances the sensitivity to the B lifetime.

The value of δ averaged over all events, i.e. summed over the 5 quark flavours is given by:

$$\langle \delta \rangle = \langle \delta_0 \rangle + \frac{\frac{4}{3} N_c f^{-1} c\tau_c + \frac{1}{3} N_b f^{-1} c\tau_b}{2N_{uds} + \frac{4}{3}N_{sec}^{c} + \frac{1}{3}N_{sec}^{b} + \frac{4}{3}N_c + \frac{1}{3}N_b} . \tag{6}$$

Here N_{uds} is the average number of charged particles produced in $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ events and $\langle \delta_0 \rangle$ is the contribution to the average impact parameter due to $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, and $K^{\pm}$, $\pi^{\pm}$ decays, $\gamma \to e^+e^-$ conversions, multiple scattering and interactions in the material in front of the tracking chambers. The number of charged particles produced in $c\bar{c}$ and $b\bar{b}$ events, in addition to those from weakly decaying charmed or bottom hadrons, are denoted by N_{sec}^{c} and N_{sec}^{b}. A Monte Carlo study at 34.6 GeV (see below) yielded $N_{uds} = 11.0$, $\langle \delta_0 \rangle = 20\ \mu m$, $N_{sec}^{c} = 8.5$ and $N_{sec}^{b} = 5.0$. With these values eq. (6) yields $\langle \delta \rangle = 20\ \mu m + 0.07\ c\tau_C + 0.04\ c\tau_B$ or $\langle \delta \rangle = 29\ \mu m + 0.04\ c\tau_B$ if an average lifetime for c hadrons of 4.5×10^{-13}s is used (see below).

As will be shown below, by applying an event shape cut the fraction of $b\bar{b}$ events can be enhanced such that $b\bar{b} : c\bar{c} : (u\bar{u} + d\bar{d} + s\bar{s}) \approx 1 : 1 : 1$. Considering only tracks with $p > 1$ GeV/c and imposing the acceptance cuts, the parameter values that enter eq. (6) are approximately given by $\langle \delta_0 \rangle = 30\ \mu m$, $N_{uds} = 3.2$, $N_c = 1.5$, $N_b = 2.9$, $N_{sec}^{c} = 1.8$ and $N_{sec}^{b} = 0.8$. This leads to $\langle \delta \rangle = 30\ \mu m + 0.07\ c\tau_C + 0.14\ c\tau_B$ or $\langle \delta \rangle \approx 39\ \mu m + 0.14\ c\tau_B$. For $\tau_B = 0.5 \times 10^{-12}$s, 1×10^{-12}s and 2×10^{-12}s one finds $\langle \delta \rangle \approx 60\ \mu m$, 81 μm and 123 μm, respectively. Provided $\tau_B > 0.5 \times 10^{-12}$s, the average impact parameter is now dominated by the bottom lifetime. In deriving eq. (6) several approximations were made. For instance the decay particles were assumed to be relativistic and the presence of the cascade decay $B \to C$ was ignored. In the analysis described below these approximations were avoided by generating Monte Carlo events and imposing the properties of the detector.

Determination of δ. The determination of δ for a single particle requires the knowledge of the beam position in the $r\varphi$ plane. At $\overline{W} = 34.6$ GeV the x and y (horizontal and vertical) coordinates of the beams were determined averaged over groups of runs using Bhabha scattering ($e^+e^- \to e^+e^-$) events. At $\overline{W} = 43.3$ GeV all beam-beam induced events were used to determine the beam position on a run by run basis. The estimated uncertainty of the average beam position was $\sigma_{\bar{x}} \simeq \sigma_{\bar{y}} \simeq 150\ \mu m$. The RMS beam size as calculated [10] from the machine parameters at $\overline{W} = 43.3$ GeV was $\sim 500\ \mu m$ in x and $\sim 10\ \mu m$ in y.

For the $\overline{W} = 34.6$ GeV data the projected impact parameter, δ, was calculated from the track reconstructed in the outer drift chamber. For momenta $p > 1$ GeV/c the RMS accuracy of δ was $\sigma_\delta \simeq 1100\ \mu$. For the $\overline{W} = 43.3$ GeV data δ was calculated from a track fit to the combined vertex detector and drift chamber hits. The RMS accuracy of δ was $\sigma_\delta \simeq 380\ \mu m$. While the resolution of δ for the drift chamber case was dominated by position resolution and multiple scattering, for the vertex detector case it was dominated by the size of the beams. Without the contribution from the beam spread the resolution would have been $\sim 100\ \mu m$. A particularly noteworthy feature of the present method is that in summing over δ for an event, the contribution of uncertainties in the interaction point, whether from uncertainty in the beam position or the beam size, tends to cancel.

b enrichment. In order to select a sample with an enriched fraction of $b\bar{b}$ events, use was made of the difference in event shape between $b\bar{b}$ events and those from $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ or $c\bar{c}$. The b quark being heavier gives rise to particles with larger transverse momenta and therefore to events with large sphericity. Large sphericity events can also arise from the production of a pair of light quarks together with a hard gluon. However, dividing these events into two hemispheres by a plane perpendicular to the sphericity axis, the sphericity is large only in one hemisphere. Thus, by selecting events with large sphericity in both hemispheres the fraction of $b\bar{b}$ events is increased. The precise criteria for selecting b enriched events were as follows. All charged particles which fell within cones of half-opening angle 41° about the sphericity axis were considered and divided into two jets of particles. The particles of each jet were boosted by a Lorentz transformation into the rest frame of a hypothetical particle travelling along the sphericity axis with velocity $\beta = 0.70$ (0.74) at $W = 34.6$ (43.4) GeV. This boost brings the particles towards the b quark rest frame. The value of β was chosen to maximize the separation of $b\bar{b}$ events from the remaining events with the help of Monte Carlo studies. The jet sphericities S_1 and S_2 of the two jets in their boosted frames were calculated. We required for the b enriched sample $S_1 \cdot S_2 > 0.1$. In total 2354 (204) events at 34.6 (43.3) GeV, or roughly 14% of all events, satisfied this condition. According to the Monte Carlo results the b enriched samples contained 32% $b\bar{b}$, 35% $c\bar{c}$ and 33% $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ events. We also defined b depleted samples by demanding $S_1 \cdot S_2 < 0.04$. These samples were composed of 6% $b\bar{b}$, 37% $c\bar{c}$ and 57% $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ events. The b depleted sample consisted of 10 322 and 879 events at 34.6 and 43.3 GeV, respectively.

We generated Monte Carlo events [11,12] according to the QCD processes $e^+e^- \to q\bar{q}$, $q\bar{q}g$, $q\bar{q}gg$ and $q\bar{q}q\bar{q}$ including all $O(\alpha_s^2)$ terms using the extended FKSS scheme [13,14], including QED radiative effects [15]. Both independent jet [16] and string fragmentation [12] were considered, employing the fragmentation parameters of our recent α_s analysis [14]. The charm and bottom quark fragmentation was described with the fragmentation function of ref. [17]. For the independent jet fragmentation scheme, the parameter ϵ_c was chosen to be 0.13 so as to yield for the average fractional energy carried by D^* mesons, $\langle E_{D^*}\rangle/E_{beam} = 0.53$, in agreement with the measured average of 0.55 ± 0.03 at CM energies >29 GeV [18]. For ϵ_b a value of 0.013 was used which leads to an average z (fraction of the energy and longitudinal momentum of the b quark) carried by the B hadrons of $\langle z_B\rangle = (E_B + p_{\parallel B})/(E_b + p_b) = 0.78$, in agreement with the experimental average of $\langle z_B\rangle = 0.77 \pm 0.05$ [19]. The lifetimes of the charmed hadrons were set equal to their measured world averages [20]: $\tau_{D^0} = 3.9$, $\tau_{D^+} = 8.2$, $\tau_F = 2.5$ and $\tau_{\Lambda_c} = 2.2$ in units of 10^{-13}s. The decay of bottom hadrons was described as follows. The B was assumed to decay via $B \to D^*$ + hadrons with a branching ratio of 80% and via $B \to \ell\bar{\nu}c$ (c = charm jet) where $\ell = e, \mu$, with a total branching ratio of 20%. The B decay was assumed to yield a D^{*0} or a D^{*+} with equal probability. The average charged particle multiplicity from B decay thus generated was 5.45, which is to be compared with $5.75 \pm 0.20 \pm 0.10$ measured for B meson decay at the $\Upsilon(4s)$ [21]. The momentum spectrum of D mesons from B-decay was modelled so as to reproduce the measured result [21]. The $b\bar{b}$ events were generated for different B lifetime values τ_B.

For each detector configuration the generated events were followed through the detector, taking multiple scattering, photon conversion, nuclear interaction and decays in flight into account and generating hits in the tracking detectors. The events were then passed through the track reconstruction, acceptance and event selection programs used for the real data.

Experimental results. In figs. 2a and 3a the impact parameter distributions for the two detector configurations are shown for b enriched events (shaded histograms) and for b depleted events (broken line histograms). For both measurements the b enriched samples show an excess of positive impact parameters, while the b depleted data are almost symmetric about $\delta = 0$. This is clearly demonstrated by figs. 2b, 2c and 3b, 3c where the normalized asymmetry $F(\delta)$,

$$F(\delta) = \Delta^{-1}[N(\delta) - N(-\delta)]/N_{tot}, \tag{7}$$

is displayed. Here $N(\delta)$ and $N(-\delta)$ are the number of tracks in the intervals $\delta \pm \frac{1}{2}\Delta$ and $-\delta \pm \frac{1}{2}\Delta$ and N_{tot} the total number of tracks with $|\delta| < 0.5$ cm. The difference between the b enriched and the b depleted data sets is striking.

The B lifetime τ_B was determined by comparing the average impact parameter $\langle\delta\rangle$ with the Monte Carlo predictions for different values of τ_B. $\langle\delta\rangle$ was obtained as the average over all tracks $|\delta| < 0.5$ cm. The

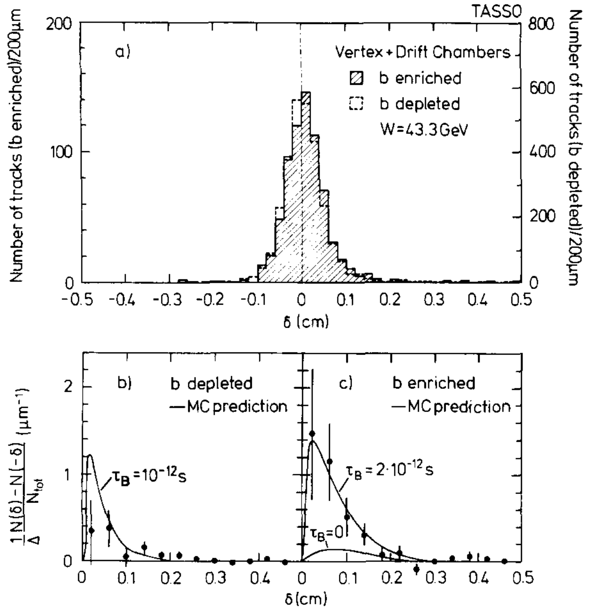

Fig. 2. (a) The distribution of the projected impact parameter, δ, for data taken with the drift chamber and vertex detector at $\bar{W} = 43.3$ GeV. Only tracks with momentum $p > 1$ GeV/c are plotted. The shaded histogram shows the b enriched data sample, the broken line histogram shows the b depleted sample. Note that the scales are different in the two cases. (b) The normalized δ asymmetry (see text) for the b depleted data. The curve shows the prediction from the Monte Carlo for $\tau_B = 2 \times 10^{-12}$s. (c) The normalized δ asymmetry for the b enriched data. The curves show the Monte Carlo expectations for $\tau_B = 0$ and $\tau_B = 2 \times 10^{-12}$s.

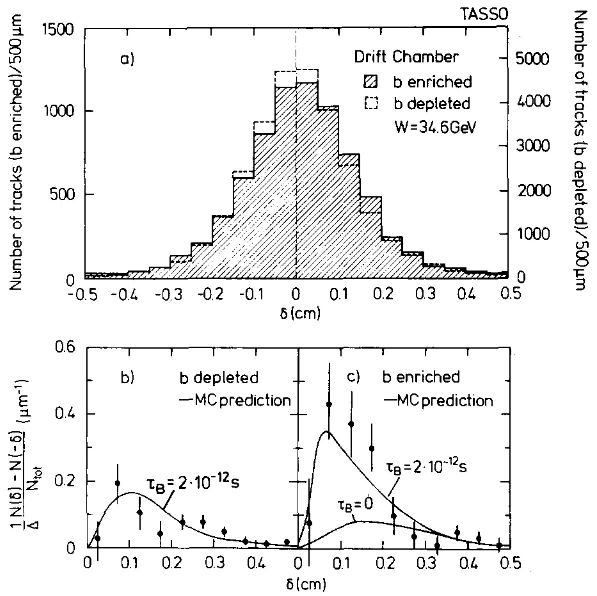

Fig. 3. (a) The distribution of δ for data taken with the drift chamber alone at $\bar{W} = 34.6$ GeV. Only tracks with momentum $p > 1$ GeV/c are plotted. The shaded histogram shows the b enriched data sample, the broken line histogram shows the b depleted data sample. Note that the scales are different in the two cases. (b) The normalized δ asymmetry for the b depleted data. The curve shows the Monte Carlo prediction for $\tau_B = 2 \times 10^{-12}$s. (c) The normalized δ asymmetry for the b enriched data. The curves show the Monte Carlo predictions for $\tau_B = 0$ and $\tau_B = 2 \times 10^{-12}$s.

Monte Carlo events were analyzed in the same way as the data. For $\langle\delta\rangle$ the results are shown in table 1. The b enriched data samples are clearly inconsistent with $\tau_B = 0$. In figs. 4a, 4b the $\langle\delta\rangle$ values measured for the b enriched samples are compared with the Monte Carlo predictions for different τ_B values. We deduce from fig. 4 the following values for τ_B:

Table 1
Comparison of $\langle\delta\rangle$ with Monte Carlo predictions for different values of τ_B.

		N_{tracks}	$\langle\delta\rangle$ (μm)	$\langle\delta\rangle_{\text{MC}}$ prediction (μm)	
				$\tau_B = 2 \times 10^{12}$s	$\tau_B = 0$
drift chamber data ($\bar{W} = 34.6$ GeV)	all events	48 800	63 ± 6	58 ± 1	41 ± 2
	b enriched	7526	105 ± 17	107 ± 5	40 ± 5
	b depleted	28 682	58 ± 8	48 ± 2	40 ± 2
vertex + drift chamber detector data ($\bar{W} = 43.3$ GeV)	all events	4 835	63 ± 9	56 ± 2	33 ± 2
	b enriched	716	109 ± 23	115 ± 6	32 ± 6
	b depleted	2 821	39 ± 12	47 ± 2	33 ± 2

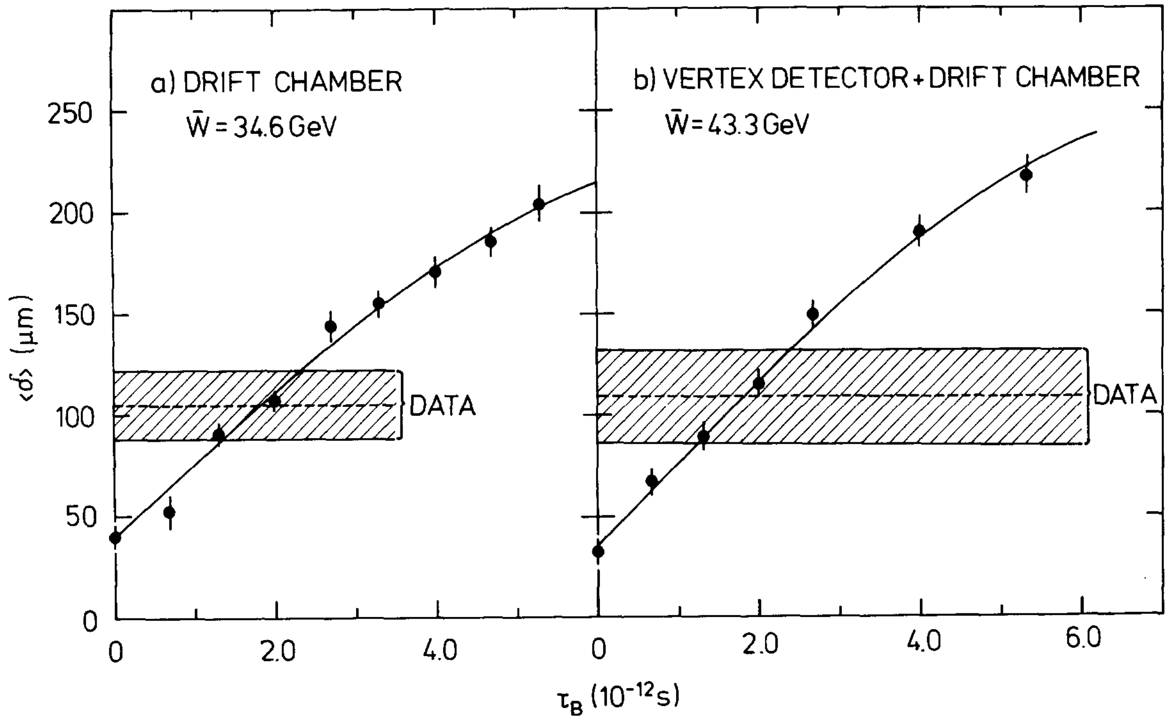

Fig. 4. (a) The $\langle\delta\rangle$ averaged over $|\delta| < 0.5$ cm, as predicted from the Monte Carlo simulation plotted as a function of the input B lifetime for the drift chamber data at $\bar{W} = 34.6$ GeV. The line shows the best fit to the Monte Carlo predictions and the shaded area shows the one standard deviation limits obtained from the data. (b) As for (a) using the vertex detector plus drift chamber data at $\bar{W} = 43.3$ GeV.

(a) drift chamber data ($\bar{W} = 34.6$ GeV):

$$\tau_B = \left(1.85 \begin{matrix} +0.49 \\ -0.48 \end{matrix}\right) \times 10^{-12}\mathrm{s}.$$

(b) vertex + drift chamber data ($\bar{W} = 43.3$ GeV):

$$\tau_B = \left(1.80 \begin{matrix} +0.58 \\ -0.57 \end{matrix}\right) \times 10^{-12}\mathrm{s}.$$

These two completely independent measurements are in excellent agreement.

Tests of the method. Since $\langle\delta\rangle$ for the b depleted data is dominated by the charm lifetime τ_C, an attempt was made to determine τ_C from them. Assuming $\tau_B = 1.8 \times 10^{-12}$s, Monte Carlo events were generated by varying the lifetimes of all charmed particles by the same fraction. The comparison of the resulting $\langle\delta\rangle$ values with the data yielded $\tau_C = (1.5 \pm 0.4)\, \tau_C^{\mathrm{nominal}}$ (drift chamber data) and $(0.8 \pm 0.60)\, \tau_C^{\mathrm{nominal}}$ (vertex + drift chamber data), leading to a combined value of $\tau_C = (1.3 \pm 0.3)\, \tau_C^{\mathrm{nominal}}$ Hence the resultant value of τ_C is consistent with the nominal value for the weighted average lifetime of D^0, D^+, F^+ and Λ_c hadrons of 4.5×10^{-13}s.

A second test was performed by determining the τ lifetime with the impact parameter method. Candidate events for the reaction $e^+e^- \to \tau^+\tau^-$ yielding final states with 4 or 6 charged particles for the decay modes $\tau^+\tau^- \to$ (1 charged) + (3 charged) and $\tau^+\tau^- \to$ (3 charged) + (3 charged) were selected as described in refs. [6,22]. A total of 346 and 48 $\tau^+\tau^-$ candidates were accepted at $\bar{W} = 34.6$ and 43.3 GeV, respectively. They yielded the following average values: $\langle\delta\rangle = 88 \pm 36$ μm (drift chamber) and 46 ± 35 μm (vertex detector + drift chamber). They are in good agreement with the values of 87 ± 8 μm and 59 ± 11 μm expected for a τ lifetime of 2.8×10^{-13}s, which is consistent with the recent measurement [6,22].

Possible instrumental biases. We searched for possible sources of systematic errors in the determination of the impact parameter. The value of $\langle\delta\rangle$ was found to be insensitive to the assumed position of the beam spot. A horizontal or vertical displacement by 200 μm changed the value of $\langle\delta\rangle$ obtained from the b enriched sample by less than 2 μm.

To check for possible misalignments of the tracking chambers we determined $\langle\delta\rangle$ separately for various subclasses of tracks: positively (negatively) charged tracks, tracks with $p_x > 0$ ($p_x < 0$), with $p_y > 0$ ($p_y < 0$) with $p_z > 0$ ($p_z < 0$). No statistically significant deviations from the average values were found. We also note that any misalignment in the tracking chambers affects the b enriched and b depleted samples in the same way and therefore cannot explain the differences between $\langle\delta\rangle$ for these data samples.

Systematic uncertainty on τ_B. Several sources contribute to the systematic uncertainty on our result for τ_B, and their effects are given below in units of 10^{-12}s.

First, uncertainty in the position of the beam spot contributes an uncertainty in $\langle\delta\rangle$ of 2 μm, corresponding to 0.05 in τ_B, as described above.

Secondly, τ_B has been extracted by calculating $\langle\delta\rangle$ for the data and Monte Carlo samples for $|\delta| < 0.5$ cm. This $|\delta|$ cut was varied between 0.4 and 0.9 cm (drift chamber data) and 0.2 to 0.8 cm (vertex detector + drift chamber data) which yielded maximum changes in the extracted values of τ_B of -0.1 and $+0.2$ respectively. We assign a possible systematic error of 0.1 due to the choice of the range of $|\delta|$.

Thirdly, in the 43.3 GeV data at least five hits in the vertex detector were demanded for a track to be accepted. The analysis was repeated by varying the minimum number of hits required in both the data and Monte Carlo samples. The maximum change in the extracted value of τ_B was +0.2 and we assign a systematic error of 0.1 due to the choice of the minimum number of hits required.

Possible instrumental errors were investigated in two ways. The quantity $\langle\delta\rangle$ was found for events from the process $e^+e^- \to e^+e^-$ + hadrons; the result was compatible with zero. The track finding problems are different in the dense jets from one-photon annihilation events and a further check is provided by a comparison of $\langle\delta\rangle$ for the b depleted sample with that predicted by the Monte Carlo; in this sample $\langle\delta\rangle$ is dominated by the relatively well-known charm lifetime (τ_C) and the quantity $\langle\delta_0\rangle$. Both the drift chamber data and the drift chamber + vertex detector data agree with the Monte Carlo within errors: any systematic shift is limited to ±6 μm, corresponding to a systematic error on τ_B of 0.15.

Finally, systematic errors in the interpretation of $\langle\delta\rangle$ due to the modelling of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ and $c\bar{c}$ events, including uncertainties in the charm lifetime and decay multiplicities yield an uncertainty in τ_B of 0.1, and uncertainties due to the fragmentation properties of b quarks and the decay spectra of B hadrons were estimated to be 0.15.

If the above estimates of systematic errors are added in quadrature, the resulting systematic error on τ_B amounts to 0.28.

There is one remaining possible source of systematic error. The relative efficiency of $b\bar{b}$ event selection in the b enrichment process can only be obtained from the Monte Carlo. The proportion of all events passing the b enrichment cut is the same, within errors, for both the Monte Carlo and the data. The calculated proportion is 13.4% with an error of no greater than ±1% due to changes in the fragmentation scheme employed. This possible error translates into possible errors of +0.25 (−0.2) in τ_B, corresponding to maximum changes of −5% (+4%) in the proportion of $b\bar{b}$ events in the enriched sample.

Adding this possible systematic error in quadrature with those from other sources listed above yields a final estimate of the systematic error of +0.37 (−0.34) on τ_B (in units of 10^{-12}s).

Combining the two measurements yields the final result:

$$\tau_B = \left(1.83 \begin{smallmatrix} +0.38 + 0.37 \\ -0.37 - 0.34 \end{smallmatrix}\right) \times 10^{-12}\mathrm{s}\,.$$

Our value is consistent with the results of the MAC group [2] of $(1.8 \pm 0.6 \pm 0.4) \times 10^{-12}$s and the MARKII group [23], $\tau_B = (1.2 ^{+0.45}_{-0.35} \pm 0.30) \times 10^{-12}$s, as well as with the preliminary result of the JADE group [24].

However, we stress again that in these three experiments semileptonic decays were selected and therefore a B lifetime measured which is weighted by the semileptonic branching ratios of the different types of B hadrons. Different B hadrons might have different semileptonic branching ratios and different lifetimes (as for D^0 versus D^+ mesons).

K–M matrix. The B-lifetime can be related [25] to the matrix elements U_{bc} and U_{bu} of the Kobayashi–Maskawa mixing matrix [26]. After correcting for phase space effects and for deviations from the free quark result the relation is [27] $\tau_B = 10^{-14}$s

$\times (3.68|U_{bc}|^2 + 7.8|U_{bu}|^2)^{-1}$. The U_{bu} contribution can be neglected since $|U_{bu}|/|U_{bc}| < 0.11$ [27]. Insertion of our lifetime value yields

$$|U_{bc}| = 0.0385 {}^{+0.0046}_{-0.0034} {}^{+0.0042}_{-0.0034} .$$

This result can also be expressed in terms of the mixing angles of Maiani [28], $|U_{bc}| = |\sin\gamma \cos\beta| \simeq |\sin\gamma|$ with good accuracy [29].

In conclusion, we have determined the average lifetime of bottom hadrons from a measurement of the average impact parameter of charged particles. Using all charged particles from B decay, rather than only the leptons from semileptonic decays increases the sensitivity to τ_B. Consistent results were obtained at two different CM energies using different detector configurations. Our final value is $\tau_B = (1.83 {}^{+0.38}_{-0.37} {}^{+0.37}_{-0.34}) \times 10^{-12}$s. This yields for the KM matrix element $|U_{bc}| = 0.0385 {}^{+0.0046}_{-0.0034} {}^{+0.0042}_{-0.0034}$.

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