Refined Measurement of the *B*-Hadron Lifetime

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We report a new measurement of the average lifetime of hadrons containing bottom quarks. The *B*-hadron decays are tagged by identifying leptons at high transverse momentum. From a fit to the lepton impact-parameter distribution, the average *B*-hadron lifetime is found to be $(0.98 \pm 0.12 \pm 0.13) \times 10^{-12}$ sec.

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The lifetime of hadrons containing bottom quarks is a measure of the strength of the weak transitions between the bottom quark and the charm and up quarks. In terms of the 3×3 quark mixing matrix proposed by Kobayashi and Maskawa,[1] the *B*-hadron lifetime depends on the magnitude of the matrix elements V_{ub} and V_{cb}. Studies of *B* semileptonic decay[2] have shown that $|V_{ub}|$ is small compared to $|V_{cb}|$, and therefore the *B* lifetime essentially measures $|V_{cb}|$ and limits $|V_{ub}|$.

The data used in this measurement were collected with the Mark II detector at the SLAC e^+e^- storage ring PEP ($E_{\mathrm{c.m.}} = 29$ GeV). We have previously reported a *B*-lifetime measurement[3] based on a data sample of 80 pb^{-1}. The present work,[4] based on a data sample of 204 pb^{-1}, includes the previous data and supersedes our earlier analysis. We use the same procedure of measuring the impact parameters of leptons produced in *B* decay. However, we have improved upon the previous result through direct measurement of the experimental resolution function, a more precise determination of the *B* production point, and a comprehensive analysis of inclusive lepton production. These improvements combined with the increased statistics make this measurement of the *B* lifetime the most precise from any experiment to data.

The Mark II detector has been described in detail elsewhere.[5] A high-resolution drift chamber, known as the vertex chamber, is situated inside the main tracking chamber. The two drift chambers are immersed in a solenoid magnetic field of 2.3 kG. Particle trajectories are measured with high precision in the (x,y) plane perpendicular to the beams, and the impact parameter is accurately determined in that plane. Electrons are identified over 64% of the solid angle with a lead–liquid-argon calorimeter. Muons are identified over 44% of the solid angle by a system of hadron absorbers and proportional tubes.

Hadronic events are selected by requiring at least six charged tracks with a scalar momentum sum greater than 7.25 GeV/c. Electron candidates must have measured momenta consistent with energies deposited in the liquid-argon calorimeter. Muon candidates are selected from particles that penetrate all four layers of iron absorber.[6] Events are selected that have lepton candidates with momenta greater than 2 GeV/c. The backgrounds in the lepton sample from beam-gas, two-photon, and $\tau^+\tau^-$ events are less than 2%. The thrust direction is calculated from all charged tracks in the event and we require $|\cos(\theta) < 0.7|$, where θ is the angle between the thrust direction and the beams.

To select events enhanced in heavy-quark production, we cut on the lepton momenta, p, and their components transverse to the thrust axes, p_t. Because the bottom hadrons are heavier than charm ones, leptons with high transverse momenta come mostly from bottom decays while those with low p_t are largely from charm decays. We define a bottom-enhanced sample as those leptons with $p > 2$ GeV/c and $p_t > 1$ GeV/c. Leptons with $p > 3$ GeV/c and $p_t < 0.75$ GeV/c comprise the charm-enhanced sample. The latter sample is used to measure the average *C*-hadron lifetime as a check on the analysis procedure. Strictly speaking, we measure the average lifetime of bottom and charm hadrons, weighted by the product of their production cross sections and semileptonic branching ratios.

The fractions of background, bottom, and charm sources in our lepton sample are determined by a fit to the inclusive lepton p and p_t spectra.[7] We find from the fit that $(64 \pm 5)\%$ of the leptons in the *b*-enhanced sample are from bottom decays, $(19 \pm 4)\%$ are from charm decays, and $(17 \pm 5)\%$ are from background. In the *c*-

enhanced sample, $(16 \pm 3)\%$ are from bottom decays, $(55 \pm 6)\%$ are from charm decays, and $(29 \pm 6)\%$ are from background.

The impact parameter is defined as the distance of closest approach of the lepton track to the production point in the plane perpendicular to the beams. The impact-parameter resolution can be written as $\sigma_\delta^2 = \sigma_\perp^2 + \sigma_p^2$, where $\sigma_\perp$ is the position resolution of the lepton track extrapolated near the origin and σ_p is the contribution from the uncertainty in the position of the production point. In our previous analysis, we used the mean beam position as an estimate of this production point, with errors based on the vertical and horizontal beam sizes, namely, 72 and 414 μm, respectively.[8] The horizontal beam size then dominates the impact-parameter resolution over much of the azimuth.

To improve the estimate of the production point over the average beam position, we include information from other tracks in the event as follows. Each event is divided into two jets by a plane perpendicular to the thrust axis. A vertex is formed from all well-measured tracks in each jet with momenta greater than 0.3 GeV/c. A well-measured track has at least three hits and a track fit in the vertex chamber with probability greater than 0.1%, and a track χ^2/N_{DF} less than 5 for the combined fit through both drift chambers. At least two such tracks are required for the jet vertex; the mean number of tracks per vertex is 3.6. The bottom or charm hadron trajectory is estimated by extrapolating from this vertex toward the beam center along the thrust direction. Errors in the thrust determination and in the location of the jet vertex are included in estimating errors in the hadron trajectory. The production point is found from a least-squares fit to the trajectory and the beam center. Use of this algorithm improves the average impact-parameter resolution from 291 to 161 μm.

The inclusion of tracks from secondary or tertiary vertices tends to move the jet vertex position along the thrust direction, rather than transverse to it, and thus influences the production-point estimate very little. Using a full detector simulation, we have verified that the production-point estimate is unbiased for hadron decay lengths less than 2.5 mm. In events with estimates of the production point from both jets we find good agreement between the two. In such events we select the estimate that gives the smaller impact-parameter error.

The thrust axis of the event serves to estimate the B- or C-hadron flight direction and to determine the impact-parameter sign. We take the hadron direction along the thrust axis as the direction making an acute angle with the lepton momentum vector. The impact parameter is signed positive if the intersection point of the lepton trajectory and the assumed hadron trajectory corresponds to a positive decay length, and is signed negative otherwise. To eliminate events where the thrust direction poorly represents the hadron flight direction, we require the event thrust magnitude to be greater than 0.75.

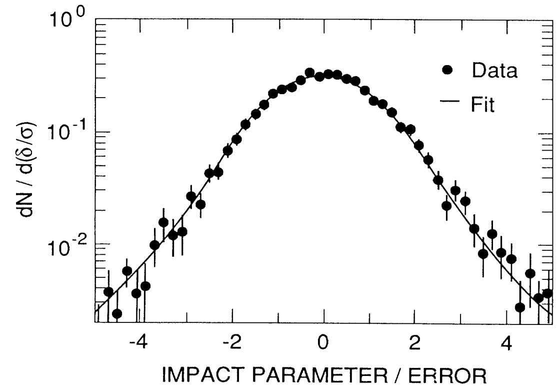

FIG. 1. Impact-parameter/error distribution for hadron tracks having small fractions of their transverse momenta in the plane perpendicular to the beams. The fitted curve represents the resolution function.

To measure the impact-parameter resolution, we select a sample of tracks in hadronic events having small fractions of their transverse momenta (relative to the thrust axis) in the plane perpendicular to the beams. This selection ensures that the projected impact parameter of these tracks due to the lifetimes of charm and bottom hadrons will be small. In the approximation that these impact parameters are negligible, this sample measures the impact-parameter resolution. The normalized distribution of impact parameters, divided by their calculated errors, is shown in Fig. 1. The resolution function is parametrized as the sum of two Gaussian functions of width 1.09 and 2.30; their relative contributions are 0.92 and 0.08, respectively.

To ensure that the lepton tracks are well measured, we require them to pass the same criteria applied to those tracks in the jet vertex. After all cuts we are left with 617 leptons in the b-enhanced sample. The measured

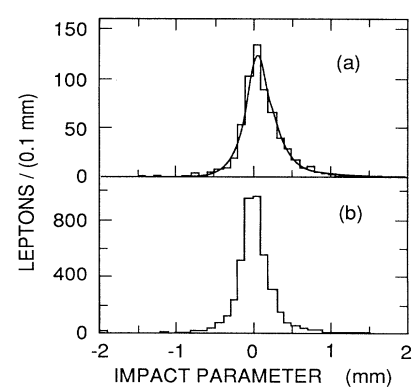

FIG. 2. Impact-parameter distributions for (a) leptons in the b-enhanced region and (b) hadrons in the same p and p_t region. The curve represents the result of the fit described in the text for the measured lifetime.

impact-parameter distribution for these leptons is shown in Fig. 2(a). The distribution has a mean of 114 ± 13 μm. The impact-parameter distribution for the 915 leptons in the c-enhanced sample has a mean of 35 ± 7 μm.

The dominant background to the lepton signal is from misidentified hadrons. We therefore measure the impact-parameter distribution for tracks not identified as leptons, weighted as a function of p and p_t by the misidentification probabilities. The impact-parameter distribution of hadron tracks satisfying the same p and p_t cuts as leptons in the b-enhanced region is shown in Fig. 2(b); it has a mean of 30 ± 5 μm. The impact-parameter distribution for muons from pion and kaon decay is studied by means of the Monte Carlo simulation. We find that the mean of this distribution is the same as that measured for misidentified hadrons but that because of the additional impact parameter generated by decay in flight, its width is increased by approximately 20%.

To determine the average B- and C-hadron lifetimes, we fit the impact-parameter distributions for leptons in the b-enhanced and c-enhanced regions simultaneously by a maximum-likelihood technique.[3] The impact-parameter fitting function is the sum of three distributions, the normalized impact-parameter distribution for background tracks weighted by the background fraction, the distribution for leptons from bottom decay weighted by the bottom fraction, and the distribution for leptons from charm decays weighted by the charm fraction.

The impact-parameter distribution for bottom and charm decays are found in two steps. We first compute the Monte Carlo–generated impact-parameter distribution for leptons from bottom and charm decays at a reference lifetime τ_0. The distribution for an arbitrary lifetime τ is found by scaling the reference distribution by the factor τ/τ_0. These distributions are determined using the LUND 6.3 hadronic event generator[9] and detector simulation that accounts for the effects of the event selection criteria. We do not include in the simulation the effects of impact-parameter resolution. These effects are properly accounted for by convoluting the Monte Carlo–generated distributions with the resolution function shown in Fig. 1. The convolutions give us the prompt-lepton impact-parameters distribution used in the fit. The width of the resolution function is scaled by the impact-parameter error calculated event by event. The background impact-parameter distribution is taken from the data shown in Fig. 2(b), normalized to the total number of events in the distribution. From the fit we determine $\tau_b = 0.98 \pm 0.12$ psec and $\tau_c = 0.74 \pm 0.13$ psec (statistical errors only). The fit to leptons in the b-enhanced region is shown in Fig. 2(a).

The average charm-hadron lifetime measured agrees well with the expected value of $\tau_c = 0.68 \pm 0.12$ psec. The expected lifetime is calculated using the measured charm lifetimes and semileptonic branching ratios,[10] and by making reasonable assumptions as to the relative proportions of D^0, D^+, and D_s^+ charm hadrons.[11] The measurement of the average charm lifetime serves as a consistency check on our analysis procedure. Variation of it from the value determined has a negligible effect on the B-hadron lifetime.

We have made a number of checks on the B-lifetime measurement. We find agreement with errors between the lifetime values measured in the electron (0.93 ± 0.15 psec) and muon (1.08 ± 0.21 psec) samples separately. To check for possible measurement bias, we determine the B lifetime using raw data from Monte Carlo–simulated events. For generated lifetime values of 0, 1, 2, and 3 psec we find values of -0.02 ± 0.05, 1.03 ± 0.05, 1.97 ± 0.07, and 2.90 ± 0.12 psec, respectively. The mean of the background impact-parameter distribution in the Monte Carlo simulation (24.6 ± 2.5 μm) agrees with the mean of the distribution seen in the data (29.6 ± 4.8 μm). As a final check, we measure the τ lifetime using the impact parameters of pion tracks from $\tau \rightarrow \pi\pi\pi\nu$ decays. The τ selection criteria have been previously discussed.[12] Employing the same production-point and impact-parameter technique as in the B-lifetime determination, we measure $\tau_\tau = 0.293 \pm 0.021 \pm 0.023$ psec. This result agrees well with the value determined from the same data sample by the decay-length method[12] and with the world average.[10]

The sources of possible systematic error in the measured B lifetime are summarized in Table I. The largest systematic errors result from uncertainties in the lepton fractions, the B-hadron fragmentation function, and the shape of the resolution function. The uncertainties in the fractions of background, bottom, and charm in our lepton sample are determined from the fit to the inclusive lepton spectra.[7] In this analysis we use a world average for the mean of the charm fragmentation function $\langle z_c \rangle = 0.68 \pm 0.06$.[13] For the bottom fragmentation function, we use $\langle z_b \rangle = 0.84 \pm 0.07$. This value agrees with our inclusive lepton analysis; we conservatively assign a large error to it. The exact shape of the resolution function used in the fit is subject to some uncertainty. We allow the amount of tail in the resolution function to change by 50% and the width of the function to change by 15%.

We have considered other potential sources of systematic error. Uncertainties in the modeling of the thrust-axis determination and in the amount of back-

TABLE I. Summary of the sources of systematic errors affecting the B-lifetime measurement.

Source	$\Delta\tau_b/\tau_b$ (%)
Lepton fractions	8.3
B- and C-hadron fragmentation	5.2
Resolution uncertainty	6.1
All other	4.2
Total	13.0

ground to the signal from the two-photon process $e^+e^- \rightarrow e^+e^- q\bar{q}$ lead to a 4% systematic error in τ_b. The possible measurement bias introduced by the production-point algorithm is found to be negligible. The systematic errors listed in Table I lead to an overall systematic error on the B-hadron lifetime of 13%.

In summary, we find the average B-hadron lifetime to be $0.98 \pm 0.12 \pm 0.13$ psec, where the first error is statistical and the second is systematic. This value is consistent with our previously published result[3] and with recent measurements from experiments at the SLAC and DESY storage rings PEP and PETRA.[14] The measurements presented in this paper and those given in Ref. 14 can be combined to yield an average B-hadron lifetime of 1.18 ± 0.12 psec. The average value is determined by weighting the individual measurements by the inverse of their statistical and systematic errors combined in quadrature. Inclusion of the measurement described in this paper lowers the average lifetime value by slightly under one standard deviation.

The measured lifetime can be used to constrain the Kobayashi-Maskawa matrix. These constraints have been discussed by numerous authors;[15] they indicate that the coupling between the third generation of quarks and the lighter quarks is weaker than that between the first two generations.

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