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Authors

Lockyer, NS
Jaros, JA
Nelson, ME
et al.

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Measurement of the Lifetime of Bottom Hadrons

N. S. Lockyer, J. A. Jaros, M. E. Nelson, G. S. Abrams, D. Amidei, A. R. Baden, C. A. Blocker, A. M. Boyarski, M. Breidenbach, P. Burchat, D. L. Burke, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup, R. J. Hollebeek, W. R. Innes, M. Jonker, I. Juricic, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, V. Lüth, C. Matteuzzi, R. A. Ong, M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman, D. Schlatter,^(a) P. D. Sheldon, J. Strait,^(b) G. H. Trilling, C. de la Vaissiere,^(c) J. M. Yelton, and C. Zaiser

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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The average lifetime of bottom hadrons was measured with the Mark II vertex detector at the storage ring PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. $\tau_b = (12.0_{-3.0}^{+4.5} \pm 3.0) \times 10^{-13}$ sec was found.

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The lifetime of bottom hadrons measures the weak coupling between the bottom quark and the charm and up quarks. By analogy to strange-particle decays, it is expected that bottom decay rates reflect quark mixing effects. In the context of the 3×3 quark mixing matrix introduced by Kobayashi and Maskawa (KM),¹ the bottom-hadron lifetime is a measure of the magnitudes of the matrix elements U_{bc} and U_{bu} . In this Letter we present a measurement of the bottom-hadron lifetime.

The data for this measurement were collected by the Mark II detector at the e^+e^- storage ring PEP located at the Stanford Linear Accelerator Center. The data sample corresponds to an integrated luminosity of about 80 pb^{-1} produced at a center-of-mass energy $E_{c.m.}$ of 29 GeV.

The Mark II detector has been described elsewhere.² We briefly describe the apparatus relevant to this analysis. A high-precision drift chamber³ (called the vertex detector) is located inside the main tracking chamber. Particle trajectories are extrapolated back to the origin with an accuracy of $100 \mu\text{m}$ transverse to the track direction. Electrons are identified over 64% of the solid angle with a lead-liquid-argon calorimeter. Muons are identified over 45% of the solid angle with a four-layered system of hadron absorber and proportional-wire chambers.

We study the bottom and charm lifetimes by measuring the projected impact parameter of leptons produced in their decays.⁴ We separate bottom from charm in a statistical sense by dividing

the lepton sample into two groups. Leptons with a large component of momentum (p_T) transverse to the thrust direction come principally from bottom decays, and those with small p_T are mostly from charm decays. Measurement of the impact-parameter distributions for each group and knowledge of the relative charm and bottom populations enable us to disentangle the lifetimes.

We search for electron and muon candidates in those events which have total charged energy exceeding $0.25E_{c.m.}$ and contain at least five charged particles, each of which passes within 5 mm of the collision point in the plane perpendicular to the beams, and within 7 cm of the collision point along the beam direction. The electron selection criteria have been described elsewhere.⁵ The hadron misidentification probability is typically 0.5%. Muons are identified as those particles whose trajectories extrapolate through all four absorbing layers and leave hits, consistent with their expected multiple scattering, in each of the proportional tube planes. The misidentification probabilities arising from hadron punch-through and decays in flight are typically 0.4% and 0.5%, respectively.

Leptons with $p_T < 1 \text{ GeV}/c$ and $p > 3 \text{ GeV}/c$ comprise the charm-enriched sample; those with $p_T > 1 \text{ GeV}/c$ and $p > 2 \text{ GeV}/c$, the bottom-enriched sample. In this analysis, the thrust direction is determined with use of all charged tracks in the event. The sine of the angle between the thrust direction and the beam direction was required to be greater than 0.7. In the b region, $(20 \pm 7)\%$ of

the lepton candidates are misidentified hadrons or pion and kaon decay products; in the c region ($34 \pm 9\%$) of the lepton candidates come from these backgrounds. From our analysis⁵ of the lepton p and p_T distributions, we find that ($80 \pm 8\%$) of the prompt leptons in the b region are from bottom decays, and ($20 \pm 8\%$) are from charm decays. In the c region, ($32 \pm 8\%$) of the prompt leptons are from bottom decays, and ($68 \pm 8\%$) are from charm decays.⁶

The impact parameter δ is taken to be the distance of closest approach between the lepton trajectory, projected in the plane perpendicular to the beams, and the beam position. We assign a positive impact parameter to the lepton if the intersection of its trajectory with the trajectory of the parent hadron corresponds to a positive decay length, and we assign it a negative impact parameter otherwise. The parent hadron is assumed to originate at the beam position, travel along the thrust direction, and decay into a forward-going lepton. Negative impact parameters may arise because the lepton trajectory and primary vertex are measured with finite precision, or because the parent has decayed backwards.

The beam position is determined run by run by finding the position which minimizes the distance of closest approach for an ensemble of tracks. In a typical 2-h run, we measure the beam position to within $20 \mu\text{m}$ vertically and $50 \mu\text{m}$ horizontally. We measure the rms beam size to be $65 \pm 15 \mu\text{m}$ vertically and $480 \pm 10 \mu\text{m}$ horizontally.

We ensure that the lepton trajectory is accurately measured by requiring a good track fit (χ^2 per degree of freedom < 4) in both the vertex detector and the main drift chamber. The error in the impact parameter, σ_δ , is dominated by the beam size and ranges from 120 to $490 \mu\text{m}$ depending on the azimuthal angle of the lepton. We require that the error be less than $350 \mu\text{m}$ which leaves 312 leptons for the remaining analysis. There are 104 lepton candidates in the b -enriched sample, and 208 in the c -enriched sample.

The measured lepton impact-parameter distributions are shown in Fig. 1(a) and 1(b) for the b -enriched and c -enriched samples, respectively. Including only those tracks which have $|\delta| < 1 \text{ mm}$, the mean of the b -enriched plot is $106 \pm 29 \mu\text{m}$ and of the c -enriched plot is $63 \pm 18 \mu\text{m}$. The dominant background for both electrons and muons is misidentified hadrons. Accordingly we have measured the impact-parameter distribution for nonleptons, weighting the sample over the

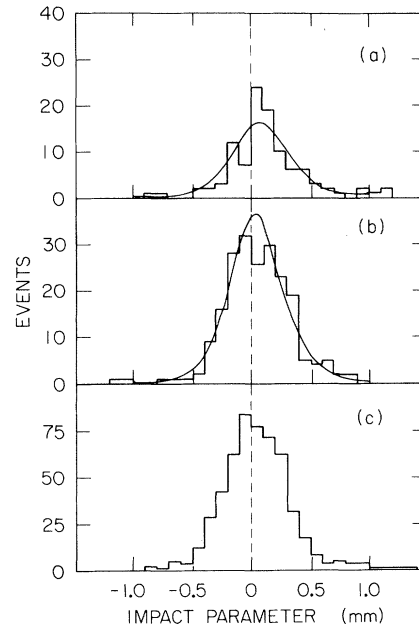


FIG. 1. Impact-parameter distributions for (a) leptons in the b region; (b) leptons in the c region; (c) hadrons in the b region. The solid curves are the result of the fit described in the text.

p, p_T space in proportion to the misidentification probability. The background from photon conversions is negligibly small because very little material (0.6% of a radiation length) precedes the tracking chambers. The impact-parameter distribution for the pion and kaon decay background is similar to that for nonleptons. The impact-parameter distribution for nonleptons in the b region is shown in Fig. 1(c). The distribution for the c -enriched sample is similar. The average impact parameter in the b -enriched region is $36 \pm 12 \mu\text{m}$ and in the c -enriched region, it is $12 \pm 7 \mu\text{m}$.

The measured impact parameters are fitted with a maximum-likelihood technique. The fitting function for a lepton in the b or c ($i=1,2$) region is the sum of distributions from three sources; background, weighted by fraction of misidentified hadrons in the sample f_{hi} ; leptons from b decays, weighted by $(1-f_{hi})f_{bi}$, where f_{bi} is the fraction of leptons from b decays; and leptons from c decays weighted by $(1-f_{hi})(1-f_{bi})$. The normalized impact-parameter distributions $dn/d\delta_i$ can be written

$$\frac{dn}{d\delta_i} = f_{hi} \frac{dn}{d\delta_{hi}} + (1-f_{hi}) \left(f_{bi} \frac{dn}{d\delta_{bi}} + (1-f_{bi}) \frac{dn}{d\delta_{ci}} \right).$$

In this expression, $dn/d\delta_{hi}$ is the measured distri-

bution of impact parameters for the background, normalized by the total number of events in the background distribution. We evaluate the normalized impact-parameter distributions for b and c decays, $dn/d\delta_{bi}$ and $dn/d\delta_{ci}$, in a two-step process. Ignoring resolution effects, we use Monte Carlo techniques to compute the impact-parameter distributions for both bottom and charm decays, in both the b -enriched and the c -enriched regions. The calculation uses the parametrization of the fragmentation functions given in Ref. 5, the known lepton decay spectra,⁷ and the effects of the selection criteria. The resulting distributions are sharply peaked at low impact parameter, have exponentially decreasing tails, and scale with the lifetime of the parent. The distributions for bottom decay show about 6% probability for small, negative impact parameters which come about because the parent has decayed backwards. The average impact parameter from b decays is about $(135 \mu\text{m})/(10^{-12} \text{ sec})$ in the b region and $(70 \mu\text{m})/(10^{-12} \text{ sec})$ in the c region; for charm decays it is about $(120 \mu\text{m})/(10^{-12} \text{ sec})$ in the b region and $(95 \mu\text{m})/(10^{-12} \text{ sec})$ in the c region. The second step in evaluating the b and c decay distributions is to convolute these primordial distributions with our experimental resolution function, a Gaussian whose width σ_δ we calculate event by event.

The result of the fit, which includes leptons with $|\delta| < 1 \text{ mm}$, is summarized in Fig. 2 which shows equal-likelihood contours in the τ_c - τ_b plane. The plot shows substantial correlation between the two lifetimes. From this analysis alone we

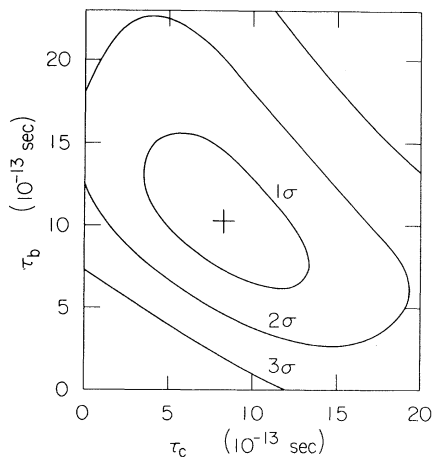


FIG. 2. Equal-likelihood contours in the τ_c - τ_b plane, corresponding to one, two, and three standard deviations from the best-fit values.

derive for the two lifetimes $\tau_b = (10.3_{-4.2}^{+5.2}) \times 10^{-13} \text{ sec}$ and $\tau_c = (8.3_{-4.8}^{+5.1}) \times 10^{-13} \text{ sec}$. We can, however, obtain a more precise value of τ_b by using world data⁹ on charm lifetimes. Taking account of the copious D^* production,⁹ of the measured lifetimes of various charmed particles, and of their various semileptonic branching ratios we estimate the appropriate average to be $\tau_c = (6.0 \pm 1.5) \times 10^{-13} \text{ sec}$. The quoted error includes the uncertainties in both individual lifetimes and relative production rates of various charmed particles. With this estimate, which agrees within errors with our own τ_c measurement, we find $\tau_b = (12.0_{-3.6}^{+4.5}) \times 10^{-13} \text{ sec}$.

We have checked our measurement technique with Monte Carlo-simulated raw data, and found that the fitted lifetimes agreed with the input lifetimes to within the statistical errors. The measured background distributions offer another check on our measurement. If we use the charm and bottom lifetimes found above in a Monte Carlo simulation, the means of the background distributions are $14 \pm 12 \mu\text{m}$ in the c region, and $37 \pm 24 \mu\text{m}$ in the b region, in good agreement with the measured values. As a final check, we determined the bottom-hadron lifetime from the electron and muon samples separately, and found that they agree within errors.

We have considered several sources of potential systematic error. Uncertainties in the background fractions, bottom-hadron fractions, fragmentation functions, and fitting procedures lead to a 25% uncertainty in the bottom-hadron lifetime.

In summary, we have measured the average lifetimes of bottom hadrons and found $\tau_b = (12.0_{-3.6}^{+4.5} \pm 3.0) \times 10^{-13} \text{ sec}$. This lifetime represents an average over bottom-hadron species, weighted by the product of their respective production cross sections and semileptonic branching ratios. Our measurement of τ_b is consistent with the value recently reported.¹⁰ The bottom-hadron lifetime imposes significant constraints on the mixing-matrix parameters,¹¹ and consequently has relevance to CP nonconservation and the top-quark mass.¹² The bottom-hadron lifetime has been related to the KM matrix elements by Gaillard and Maiani¹³:

$$\tau_b = \tau_b^0 / (2.75 |U_{bc}|^2 + 7.7 |U_{bu}|^2).$$

Here $\tau_b^0 = \tau_\mu (m_\mu/m_b)^5$, where τ_μ is the muon lifetime and m_μ/m_b is the ratio of the muon and b -quark masses. From studies of the lepton spectrum in b decay,¹⁴ it is known that $|U_{bu}|^2 < 0.02$

$\times |U_{bc}|^2$, so that the U_{bu} term in the expression for the lifetime is negligible. If we put $m_b = 5$ GeV/ c^2 , we find $|U_{bc}| = 0.053_{-0.009}^{+0.010}$, where the error is statistical only. This value is appreciably smaller than that of the analogous matrix element which describes strange-particle decay, $U_{su} = 0.22$, the sine of the Cabibbo angle.

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^(a)Present address: CERN, CH-1211 Geneva 23, Switzerland.

^(b)Present address: University of Massachusetts, Amherst, Mass. 01002.

^(c)Present address: Laboratoire de Physique Nucléaire et Hautes Energies, Université Pierre et Marie Curie, F-75230 Paris, France.

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