Lifetime of Particles Containing b Quarks

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From a sample of hadronic events produced in e^+e^- collisions, semileptonic decays of heavy particles have been isolated and used to obtain a measurement for the bottom-quark lifetime of $[1.8 \pm 0.6\text{ (stat.)} \pm 0.4\text{(syst.)}] \times 10^{-12}$ sec.

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According to the standard six-quark model, the decay of the lowest-lying bottom-flavored hadrons is forbidden in the absence of mixing of b quarks with either s or d quarks (or both). The values of mixing angles, as defined, for example, by Kobayashi and Maskawa[1] or by Maiani,[2] can be constrained by a measurement of the b lifetime. In the present experiment semileptonic decays have been used to isolate bottom-flavored particles, produced in e^+e^- annihilations to hadrons, and to determine the average lifetime of the resulting mixture of these states. Earlier measurements led to upper limits,[3] of which the most stringent is $\tau_b < 1.4 \times 10^{-12}$ sec, reported by the JADE Collaboration.

The MAC detector,[4,5] operating at the PEP storage ring at the Stanford Linear Accelerator Center, includes a cylindrical drift chamber for tracking charged particles, consisting of ten layers of drift wires in a solenoidal magnetic field of 5.7 kG. The radii of the inner- and outermost layers are 12 and 45 cm, respectively, and the point measurement accuracy is about 200 μm. The drift chamber is surrounded by electromagnetic and hadron calorimeters. Layers of lead interspersed with proportional wire chambers constitute the electromagnetic shower chamber, amounting to 16 radiation lengths of material. In the hadron calorimeter, layers of steel alternate with proportional wire chambers, such that normally incident particles traverse 91 cm of steel. Two end-cap calorimeters, alternating steel and proportional chambers, cover angles greater than 10 deg from the beam. The solid angle subtended by calorimeters is therefore about 98% of 4π. The calorimeter steel in both the central and end-cap regions is magnetized to about 17 kG by toroid coils. The entire calorimetric detector is surrounded by drift chambers for muon tracking. These chambers determine the radial and axial components of the location and direction of particles penetrating the hadron calorimeters.

The parent sample for this analysis consists of approximately 50 000 multihadron events having five or more charged prongs and calorimetric energy flow consistent with production by single photon annihilation. Cuts on the total energy, its component perpendicular to the beam, and the net energy imbalance eliminate two-photon annihilation events.[5,6] The muon (electron) sample corresponds to an integrated luminosity of 108 (92) pb^{-1} at a center-of-mass energy of 29 GeV.

Within these events, muon candidates were reconstructed and momentum analyzed by interpolation between isolated track segments in the outer drift chambers and the primary event vertex, through the toroidal magnetic field of the calorimeter, taking into account the ionization energy loss of the particle in the calorimeter. It was required that the resulting track be matched within typically 1° in polar angle and 30% in momentum to a track reconstructed in the central drift chamber, and within 2 to 10 deg to a segment reconstructed from the energy deposited in the central or end-cap calorimeter. (The actual cuts were made on the appropriate χ^2, computed with inclusion of all measurement errors and the effect of multiple scattering, and are momentum dependent.) It was required that the calorimeter pulse heights correspond to those of a single minimum-ionizing track.

An electron candidate is defined as a track in the central drift chamber associated with a shower in the electromagnetic shower chamber and with no significant energy deposition in the hadron calorimeter. Only tracks with momentum greater than 1.8 GeV/c and in the fiducial region $|\cos\theta| < 0.7$ are considered. The energy deposited in the calorimeters is measured in a 2° (azimuthal) × 5° (polar) cone around the direction of the track at the exit of the drift chamber and is required to follow a pattern typical of the development of an electromagnetic shower in our detector, as determined from nonradiative and radiative Bhabha events. The contamination in the sample, apart from c-quark semileptonic decays, comes from e^+e^- pairs (photons converting in the vacuum pipe and Dalitz pairs), τ and ψ decays, and hadron misidentification. About 50% of the electron pairs can be easily identified; the remaining contamination has been calculated not to exceed 25% of the sample.

To estimate the background in both samples and to study heavy-flavor decay, we have constructed a Monte Carlo model to simulate the production and decay of hadrons[7] and to trace in detail their interactions and the response of the detector.[8]

In a previous publication[6] we presented a measurement of the fragmentation function of b quarks. As described in detail there, discrimination between heavy and light quarks that decay to leptons is achieved via the total momentum of the lepton and by its component perpendicular to the thrust axis of the event ($p_\perp$): A heavy hadron follows closely the direction of the primary quark which in turn is well approximated by the thrust axis. On decay, the heavy parent imparts a large transverse momentum to the daughter lepton. The specific cuts applied in the present analysis were total momentum greater than 2 GeV/c and $p_\perp$ greater than 1.5 GeV/c.

The lifetime of the particles which decay to produce the observed leptons is inferred from the distribution in impact parameter of the lepton tracks with respect to the interaction point. In Fig. 1 are defined the flight path, l, of the parent hadron (e.g., B meson), the directions of travel of the parent and lepton (e.g., muon), the decay angle ψ, and the impact parameter δ, all as projected onto a plane perpendicular to the beam axis. The quantity δ is taken to be positive (negative) in the reconstructed events (where the B direction is unknown) if a forward (backward) laboratory decay angle would be inferred for the lepton, under the assumption that the parent traveled along the thrust axis toward its intersection with the muon trajectory. The effect of approximating the B direction by the thrust axis is to cause a true positive δ to appear negative when the angle of the muon trajectory falls between those of the B flight path and the thrust axis, diluting the observed effect. Detailed calculations show that the resulting loss of sensitivity from this effect is negligible for b particles and about a factor of 3

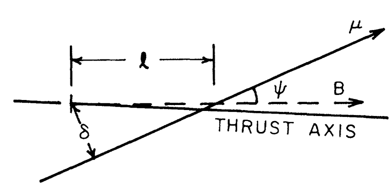

FIG. 1. Direction vectors and production and decay points relevant to heavy-hadron leptonic decay.

for charm. On the other hand, for π and K decay and converted gamma ray backgrounds there is nearly complete cancellation.

The average value of δ computed from the observed distribution is proportional to the lifetime:

$$\langle \delta \rangle = \langle \beta\gamma \sin\psi \sin\theta \rangle c\tau \equiv \alpha c\tau, \qquad (1)$$

where θ is the polar angle of the track. The constant α, computed with the Monte Carlo program, is about 0.45 (0.15) for bottom (charm). It is found to be very insensitive to the fragmentation function. Typically, the decay angle ψ shrinks as a function of parent momentum at about the same rate that the relativistic time dilation factor grows. The detailed calculation shows that α decreases by 11% as the average B momentum is changed from 0.8 to 0.5 times the beam momentum.

The precision of the measurement of δ is determined by the precision of the extrapolation of the lepton track reconstructed in the central drift chamber, and by the effective size of the beam interaction volume, including the effect of any uncorrected shifts with time of the beam position. The beam position for each run was determined by a simultaneous fit to all of the Bhabha events in that run. A plot of the results as a function of time was then used to establish beam-position values for each block of runs between significant changes. From these data we find the effective rms beam size to be about 0.4 mm (horizontal) by 0.1 mm (vertical). The uncertainty of the track extrapolation came from propagation of the point measurement error, which in turn was established from χ^2 distributions for track fits. Figure 2 shows the distribution in the uncertainty of δ; events having uncertainty less than 1 mm are entered into the histograms of δ, Fig. 3, weighted by the corresponding reciprocal squared errors. The mean values $\langle\delta\rangle$ from these distributions are listed in Table I.

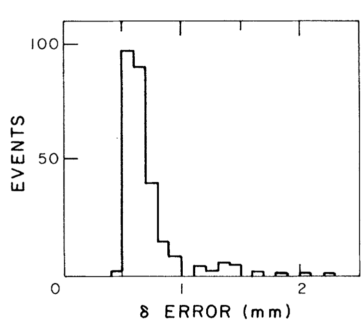

FIG. 2. Distribution of measurement uncertainties of the decay impact parameter, δ.

In terms of the separate components of the data sample, the average value of δ is given by

$$\langle \boldsymbol{\delta} \rangle = f_b\, \alpha c\tau_b + f_c\, \delta_c + f_{bg}\delta_{bg}. \qquad (2)$$

Here the subscripts b, c, and bg refer to b- and c-flavored particles and to background, respectively; f_i is the fraction of the sample corresponding to component i; and the factor α is defined in Eq. (1). Here f_c includes cascades $b \to c \to$ lepton. The values of these parameters, given with their uncertainties in Table I, were determined from the Monte Carlo program. The QCD and fragmentation parameters in the model were adjusted to fit measured hadron-production spectra,[5] including energy-energy correlations[5] and the fragmentation of heavy flavor as measured with the momentum and $p_\perp$ distributions for inclusive leptons.[6,9,10] The b leptonic branching fraction used was 15%, as measured previously[6] with a sample partially overlapping the present one. The charm leptonic branching fraction was taken to be[10,11] 8%, and the lifetimes of charmed particles used in the calculation, in units of 10^{-13} sec, are[12] (D^0) 4.0; ($D^\pm$) 9.3; ($F^\pm$) 2.9 (population-weighted average = 5.5).

From Table I it can be seen that the expected values of $\langle\delta\rangle$ for charmed-particle decays and for background are around 20–30 μm; their contribution to the signal when weighted by the corresponding fractions is thus of order 5–10 μm, compared with the observed values of about 160 μm for both data samples. There is evidence in Fig. 3(a) of a contribution at large $|\boldsymbol{\delta}|$ from the decay of π and K mesons to muons; these events

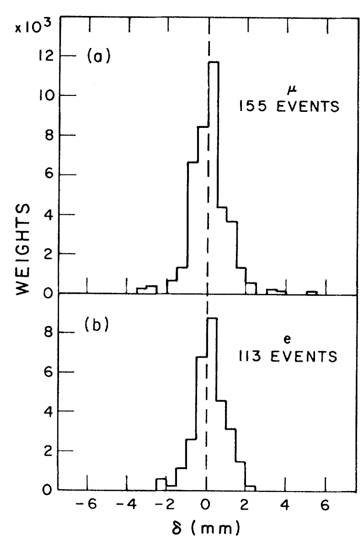

FIG. 3. Distribution of δ for (a) muons and (b) electrons.

TABLE I. Summary of parameters used to compute τ_b.

Sample	No. of events	f_b	f_c	f_{bg}	δ_c (μm)	δ_{bg} (μm)	α	$\langle\delta\rangle$ (μm)	τ_b (10^{-12} sec)
μ	155	0.72 ± 0.08	0.14 ± 0.04	0.14 ± 0.07	24 ± 11	26 ± 8	0.43 ± 0.03	158 ± 81	1.62 ± 0.87
e	133	0.63 ± 0.07	0.12 ± 0.05	0.25 ± 0.08	19 ± 11	24 ± 6	0.46 ± 0.03	174 ± 75	2.00 ± 0.84

add to the standard deviation of the distribution, but not significantly to the mean, as we have confirmed by relaxing cuts to admit more decay events.

As a check for bias in the distribution of δ a control sample was made from the parent multihadron sample by taking all charged-particle tracks (including leptons) assigned to the primary vertex which pass the same momentum and $p_\perp$ cuts required for the data sample. Momentum and $p_\perp$ distributions of the surviving events are quite similar to those of the data sample. The resulting weighted $\langle\delta\rangle$ for 18093 tracks is 34 ± 8 μm, to be compared with 24 ± 6 μm (of which 16 ±6 μm is due to b particles) expected from short-lived particles in the control sample. We conclude that the observed nonzero $\langle\delta\rangle$ in the data samples is to be attributed mainly to the term proportional to τ_b in Eq. (2). This conclusion is insensitive to the uncertainties in f_c, δ_c, f_{bg}, and δ_{bg}. Assigning a systematic uncertainty of 30 μm for $\langle\delta\rangle$ and combining with the other systematic errors quoted in Table I we finally find

$$\tau_b = (1.8\pm0.6\pm0.4)\times10^{-12}\text{ sec},$$

where the first error quoted is statistical and the second is systematic. This is the first nonzero result reported for τ_b.

In terms of the mixing angles of Maiani,[2] the standard-model prediction for τ_b is given by[13]

$$\frac{1}{\tau_b} \simeq 1.08\times10^{14}\left(\frac{m_b}{5\text{ GeV}}\right)^5 \times(2.75\sin^2\gamma+7.69\sin^2\beta)\text{ sec}^{-1}.$$

With the assumption $m_b = 5$ GeV/c^2, and in combination with the measured upper limit of 0.055 for the noncharm branching fraction of b particles,[14] our result for τ_b implies $|\sin\gamma| = 0.04$ ±0.01.

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[1]M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[2]L. Maiani, in *Proceedings of the Eighth International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1977*, edited by F. Gutbrod (DESY, Hamburg, Germany, 1977).

[3]W. Bartel *et al.*, Phys. Lett. 114B, 71 (1982); D. M. Ritson, J. Phys. (Paris), Colloq. 43, C3-52 (1982).

[4]MAC Collaboration, in *Proceedings of the International Conference on Instrumentation for Colliding Beams*, edited by W. Ash, SLAC Report No. SLAC-250 (SLAC, Stanford, 1982), p. 174; W. T. Ford *et al.*, Phys. Rev. Lett. 49, 106 (1982); Roy Weinstein, in *Particles and Fields—1982*, edited by W. E. Caswell and G. A. Snow, AIP Conference Proceedings No. 98 (American Institute of Physics, New York, 1982); G. Gidal, B. Armstrong, and A. Rittenberg, Lawrence Berkeley Laboratory Report No. LBL-91 Suppl., 1983 (to be published).

[5]B. K. Heltsley, Ph.D. thesis, University of Wisconsin Report No. WISC-EX-83/233, 1983 (unpublished).

[6]E. Fernandez *et al.*, Phys. Rev. Lett. 50, 2054 (1983).

[7]T. Sjostrand, Comput. Phys. Commun. 27, 243 (1982), and Lund University Report No. LU TP-82-7, 1982 (unpublished).

[8]Electromagnetic showers are simulated by EGS, described in R. L. Ford and W. R. Nelson, SLAC Report No. SLAC-210, 1978 (unpublished). Hadronic cascades are simulated by HETC, described in T. W. Armstrong, in *Computer Techniques in Radiation Transport and Dosimetry*, edited by W. R. Nelson and T. M. Jenkins (Plenum, New York, 1980).

[9]D. Schlatter, SLAC Report No. SLAC-PUB-2982, 1982 (unpublished).

[10]M. E. Nelson *et al.*, Phys. Rev. Lett. 50, 1542 (1983).

[11]R. Brandelik *et al.*, Phys. Lett. 70B, 387 (1977); R. Schindler *et al.*, Phys. Rev. D 24, 78 (1981); W. Bacino *et al.*, Phys. Rev. Lett. 43, 1073 (1979), and 45, 329 (1980); J. M. Feller *et al.*, Phys. Rev. Lett. 40, 274, 1677 (1978).

[12]G. Kalmus, J. Phys. (Paris), Colloq. 43, C3-431 (1982), and references therein.

[13]M. Gaillard and L. Maiani, in *Proceedings of the 1979 Cargese Summer Institute on Quarks and Leptons*, edited by M. Levy *et al.* (Plenum, New York, 1979), p. 433

[14]C. Klopfenstein *et al.*, Columbia University/Stony Brook Report No. CUSB 83-03 (to be published).