Determination of the Lifetime of Bottom Hadrons

W. W. Ash, H. R. Band, E. D. Bloom, M. Bosman,[a] T. Camporesi,[b] G. B. Chadwick, M. C. Delfino, R. De Sangro, W. T. Ford, M. W. Gettner, G. P. Goderre,[c] G. L. Godfrey, D. E. Groom, R. B. Hurst, J. R. Johnson, K. H. Lau, T. L. Lavine, R. E. Leedy, I. Lippi,[d] T. Maruyama, R. L. Messner, J. H. Moromisato, L. J. Moss, F. Muller,[b] H. N. Nelson, I. Peruzzi, M. Piccolo, R. Prepost, J. Pyrlik, N. Qi, A. L. Read, Jr.,[e] D. M. Ritson, L. J. Rosenberg,[f] W. D. Shambroom,[g] J. C. Sleeman, J. G. Smith, J. P. Venuti, P. G. Verdini, E. von Goeler, H. B. Wald, R. Weinstein, D. E. Wiser, and R. W. Zdarko

Department of Physics, University of Colorado, Boulder, Colorado 80309
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Frascati, Italy
Department of Physics, University of Houston, Houston, Texas 77004
Department of Physics, Northeastern University, Boston, Massachusetts 02115
Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
Department of Physics, University of Utah, Salt Lake City, Utah 84112
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

(Received 27 October 1986)

We have measured the mean lifetime of the hadrons containing b quarks that are produced in e^+e^- annihilation at $\sqrt{s} = 29$ GeV. We use the full sample of data collected by the MAC detector at the SLAC storage ring PEP, including those recently acquired with a precision vertex detector. The result is $\tau_b = [1.29 \pm 0.20(\text{stat}) \pm 0.07(\text{syst})\ \text{ps}] \times (1.00 \pm 0.15)$, where the last factor is the systematic uncertainty in the scale.

PACS numbers: 13.20.Jf, 13.30.Ce

The fact that the mean lifetime of hadrons containing b quarks, or B hadrons, is long enough to be measured at presently accessible energies shows that the third quark generation is more weakly coupled to the first two generations than the latter are to each other. This is usually expressed quantitatively in terms of the smallness of the Kobayashi-Maskawa matrix elements U_{cb} and U_{ub}, which determine the transition rate for a b quark to decay weakly to a c or u quark.[1] Interest in the fundamental parameters U_{cb} and U_{ub} has led detector groups at e^+e^- colliders to measure B lifetimes and branching ratios.

Results from the SLAC and DESY storage rings PEP and PETRA for the B lifetime range from 0.8 to 1.8 ps.[2-4] A recently observed event from the CERN triggered-emulsion experiment provides evidence for a B lifetime ~ 0.3 ps.[5] With the installation of a high-precision vertex chamber having small inner diameter in the MAC detector at PEP, an improved lifetime measurement has become possible. New analysis techniques have been developed to make optimal use of the tracking information, both for data collected after installation of the vertex chamber, and for those collected previously.

A detailed description of the MAC detector can be found elsewhere.[6] A brief discussion of the components important to this measurement is given here. Figure 1 shows the tracking chambers projected onto a plane containing the beam axis. The central detector (CD) is a ten-layer drift chamber in an axial magnetic field of 5.7 kG, with six layers at angles of ± 3° to the beam axis, and with the first and last layers at radii of 12 and 45 cm, respectively. Figure 1 also shows the location of the vertex chamber (VC), which has been described elsewhere.[7] Space was created for the VC by reduction of the radius of the beam pipe from 8.8 to 3.6 cm. Despite the proximity of the beam pipe wall to the beam, only two background hits per beam crossing are observed on average in the VC. The VC consists of 324 thin-walled axial drift tubes arranged in three double layers. The tubes are enclosed in a gas vessel containing a mixture of 50% argon, 49% CO_2, and 1% methane at a pressure of 4 atm. Each drift tube typically provides a position resolution of 50 μm. The resolution in impact parameter, the distance of closest approach to the beam centroid in the plane transverse to the beam, is 390 μm for data prior to VC installation and 90 μm with VC operational, as measured with Bhabha scattering events. Multiple scattering in the beam pipe and chamber wall adds (360 μm

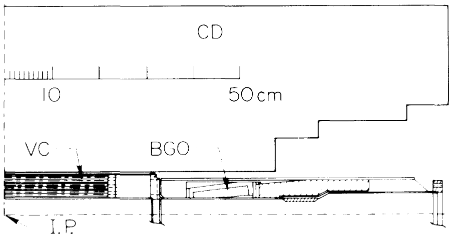

FIG. 1. Layout of the central tracking chamber and vertex detector relative to the beam pipe, shielding, and active bismuth germanate (BGO) shielding. The devices are symmetric about the beam axis.

GeV)/p before and (65 μm GeV)/p after VC installation.

The barrel calorimeter of MAC has an electromagnetic shower detector of lead interspersed with proportional wire chambers, comprising a total of 14 radiation lengths. The hadronic barrel and end-cap calorimeters are constructed of alternating layers of steel and gas proportional tubes, with normally incident particles traversing 90 cm of steel corresponding to ~5 nuclear interaction lengths. The calorimeters cover 98% of the full solid angle. The small inner diameter of the calorimeter minimizes the path length available for decay of pions and kaons into muons. The steel of the hadronic calorimeter is toroidally magnetized to 17 kG. The entire calorimetric detector is surrounded by an outer drift-chamber system (OD) consisting of four to six layers of 10-cm-diam drift tubes that measure the exit polar angles of muons traversing the steel, and consequently muon momenta, to ~25%.

The data samples for the analysis were accumulated at $\sqrt{s}=29$ GeV and consist of an integrated luminosity of 220 pb^{-1} collected without the vertex chamber, and 94 pb^{-1} from the running with the VC installed. A sample of hadronic events enriched in B-hadron decays is selected by the requirement of a muon or electron with large transverse momentum with respect to the event thrust axis, which approximates the initial B direction. For each event the B-production point is approximated by the weighted average of the beam centroid, determined from Bhabha-scattering events, and information from high-quality tracks. The impact parameter with respect to this average vertex is evaluated and given a sign. A positive impact parameter indicates a forward and nonzero flight path of the B hadron. Negative impact parameters result from the appearance, usually due to imperfect resolution, that the parent hadron proceeded backward. Not just the lepton tracks that tagged the events, but all tracks with sufficient momentum and measurement quality are used in the present analysis to provide impact parameters.

Candidate events with a muon or electron having momentum greater than 2 GeV/c are selected from a one-photon–annihilation hadronic event sample.[8] For muons, an OD track is required to link to a clean set of hits in the outer calorimeter layers. The combined OD and calorimeter information is then required to match a CD track within 4.0° in polar angle, 4.5° in azimuth, and 60% in momentum. For electrons, a match between a shower in the barrel electromagnetic calorimeter and a CD track is required, as well as no appreciable energy deposition in the hadronic calorimeter. Further, the shower transverse and longitudinal energy deposition is required to be consistent with an electromagnetic shower.[2]

Events are then selected according to thrust information,[9] calculated from the calorimeter data. For events containing muons, corrections from tracking information compensate for the energy of the muon not deposited in the calorimeters. The thrust axis is required to be greater than 30° from the beam direction, and the thrust is required to exceed 0.72 to ensure that the axis is well defined. Events are required to contain a lepton with momentum transverse to the thrust axis of greater than 1.5 GeV/c, a requirement that provides enrichment in $b\bar{b}$ production events.[10] Electrons are further required to have momentum components greater than 1.2 GeV/c perpendicular to the thrust axis in the plane transverse to the beam direction to eliminate two-photon annihilation events. The preceding requirements select 336 muon- and 74 electron-tagged multihadron events from data with the CD only, and 117 muon and 35 electron events from data with both CD and VC.

Tracks used to provide impact parameters and/or estimate the B-production point are required to have momentum greater than 0.5 GeV/c and at least seven hits in the CD. For data taken with the VC, at least three hits are required in the VC. Tracks used to find the average vertex are further required to have the absolute value of the impact parameter relative to the beam centroid less than 1 mm. The statistical weights of these tracks are taken from the covariance matrix of the fitting procedure, while the weight of the beam centroid is determined from its spatial standard deviation measured in Bhabha-scattering events, 70 μm vertically and 350 μm horizontally. Tracks providing impact parameters are required to be separated from the thrust axis by the angle greater than (0.2 rad)/$\sin\theta_t$ in the plane transverse to the beam, where θ_t is the angle between the thrust axis and the beam. This requirement both reduces sensitivity to errors in thrust-axis determination and eliminates tracks containing little information about the B-hadron path length. The average vertex is computed with omission of the track for which the impact parameter is being measured. Tracks with impact parameters greater than 4 mm in the data without the VC and greater than 3 mm in the subsequent data are excluded to reduce bias and fluctuation from K^0 and Λ decays. The final sample consists of 1558 tracks in the data prior to VC installation and 441 tracks in subsequent data.

Figure 2 shows distributions of impact parameter measured relative to the beam center and relative to the average vertex, for both untagged and lepton-tagged multihadron events. The lepton-tagged data taken after VC installation show not only a positive displacement but also an exponential-like tail.

The trimmed mean of the impact-parameter distribution is used as a robust statistical estimator of the lifetime.[11] The trimmed mean X is defined as the mean of a distribution from which fractions f, in the tails, have been symmetrically removed. Good precision for the experimental impact-parameter distributions is obtained with $f=0.1$. The statistical error of the trimmed mean

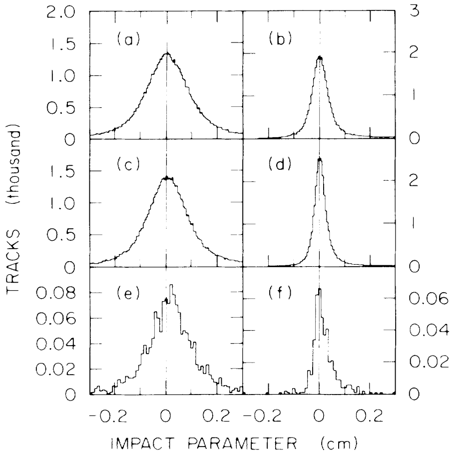

FIG. 2. Impact-parameter distributions for (a) untagged multihadron data collected before installation of the VC with impact parameters measured relative to the beam centroid; (b) similar data after VC installation; (c) same as (a), taken relative to the average vertex; (d) same as (b), taken relative to the average vertex; (e) lepton-tagged data before installation of the VC and measured relative to the average vertex; (f) similar data after VC installation.

is determined from the sample distribution. The lepton-tagged data collected prior to VC installation yield a trimmed mean of 154 ± 26 μm, and later data give 129 ± 19 μm.

Lifetimes are determined by our finding the value required by the Monte Carlo simulation to produce trimmed means equal to those in the data. The Monte Carlo generator[12] used for the hadronization simulation is the Lund code with the string option and heavy-quark fragmentation functions given by Peterson *et al.*[13] For heavy-quark events the Peterson fragmentation parameters ε_c and ε_b are taken to be 0.063 and 0.012, respectively. Typical lifetimes used in the Monte Carlo program are $\tau_b = 1.2$ ps, $\tau_{D^0} = 0.44$ ps, $\tau_{D^+} = 0.85$ ps, $T_{\Lambda_c} = 0.23$ ps, and $\tau_{D_s} = 0.19$ ps. The Monte Carlo computation predicts that 70% of the tracks in the lepton-tagged samples come from $b\bar{b}$ production, 16% from $c\bar{c}$ production, and 14% from light-quark production. The respective contributions to the trimmed mean are $X_b \approx 180$ μm, $X_c \approx 25$ μm, and $X_{uds} \approx 10$ μm.

The B lifetime determined from the data without the VC is $\tau_b = 1.24 \pm 0.29(\mathrm{stat})$ ps. Data collected with the VC give $\tau_b = 1.35 \pm 0.30(\mathrm{stat})$ ps. The complete electron sample yields $\tau_b = 0.92 \pm 0.35(\mathrm{stat})$ ps, while the muon sample yields $\tau_b = 1.30 \pm 0.25(\mathrm{stat})$ ps. The combined result is $\tau_b = 1.29 \pm 0.20(\mathrm{stat})$ ps.

Measurement systematic errors have been studied in five ways. First, impact parameters of the lepton-tagged sample and a large control sample of untagged multihadrons are given signs from a geometric convention, without reference to the thrust axis. The resulting trimmed means are consistent with zero. Second, by use of the same technique, the τ lifetime has been measured: Data accumulated with the VC yield a lifetime[14] in excellent agreement with the current world average of 0.290 ± 0.017 ps.[15] The remaining three tests rely on the ability of the MAC Monte Carlo program to model detector performance. By our setting all lifetimes equal to zero in the Monte Carlo simulation it was verified that the reconstructed impact-parameter distribution was not offset and was symmetric. The trimmed means of the control sample and Monte Carlo–generated multihadrons agree to within 10 μm for variations of the impact-parameter cut from 1 to 10 mm and of the trim factor f from 0.0 to 0.5. Finally, the average vertex was replaced by the beam centroid in both data and Monte Carlo simulation. The measurement systematic error estimated from these studies is an additive error of 0.05 ps and a multiplicative error of ± 7%.

With the trimmed mean X approximated as $f_bX_b + f_cX_c + f_{uds}X_{uds}$, systematic errors due to model dependence of the fragmentation calculation are contributed dominantly through the term f_bX_b. The subscripts b, c, and uds refer, respectively, to b, c, and light-quark events; f_i is the fraction of tracks in the data arising from quark type i, and X_i the trimmed mean. Uncertainty in X_b arises from uncertainty in b-quark fragmentation. Taking the mean fraction of beam energy retained by the B hadron, corrected for initial state radiation, to be 0.78 ± 0.05[16] indicates an error in X_b of ± 10%, multiplicative in τ_b. Uncertainty in f_b arises from the uncertainties in (1) the mean leptonic branching ratio of B hadrons [taken to be[15] $(12 \pm 1)\%$]; (2) b- and c-quark fragmentation; and (3) detector efficiency. The total f_b systematic uncertainty contribution is ± 7%. Uncertainties in D, D_s, and Λ_c lifetimes contribute a 0.05-ps systematic error. Addition of all systematic errors in quadrature gives an additive error in τ_b of ± 0.07 ps and a multiplicative error of ± 15%.

The combined value for the B lifetime, based on the results given above, is $\tau_b = 1.29 \pm 0.20(\mathrm{stat}) \pm 0.07(\mathrm{syst})$ ps, with a systematic multiplicative uncertainty of ± 15%. This value is in agreement with the world average from PEP and PETRA detectors, $\tau_b = 1.26 \pm 0.16$ ps,[15] where statistical and systematic errors have been combined in quadrature.

We gratefully acknowledge the help of the PEP and MAC Operations groups and in particular that of N. Palmer and D. Wright in the Vacuum Group of the Klystrons Task Force. We also wish to thank E. Askeland, J. Broeder, N. Erickson, J. Escalera, and J. Schroeder for their superb technical work on the vertex chamber construction. We would especially like to thank and remember the late C. T. Pulliam, who was the engineer responsible for the mechanical fabrication and installation of the vertex chamber. This work was supported in part by the U.S. Department of Energy under Contracts No. DE-AC02-81ER40025 (University of Colorado), No. DE-AC03-76SF00515 (Stanford Linear

Accelerator Center), and No. DE-AC02-76ER00881 (University of Wisconsin); by the National Science Foundation under Grants No. NSF-PHY82-15133 (University of Houston), No. NSF-PHY82-15413 and No. NSF-PHY82-15414 (Northeastern University), and No. NSF-PHY83-08135 (University of Utah); and by the Istituto Nazionale di fisica Nucleare.

(a)Present address: Max-Planck-Institut, Munich, Federal Republic of Germany.

(b)Present address: CERN, Geneva, Switzerland.

(c)Present address: Texas Accelerator Center, The Woodlands, TX 77380.

(d)Permanent address: Physics Department, University of Padua, Padua, Italy.

(e)Present address: University of Oslo, N-0316 Oslo 3, Norway.

(f)Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL 60637.

(g)Joint appointment: Department of Physics and College of Computer Science, Northeastern University, Boston MA 02115.

[1] M. Kobayashi and K. Maskawa, Prog. Theor. Phys. **49**, 652 (1973); L. Maiani, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energy, Hamburg, 1977,* edited by F. Gutbrod (DESY, Hamburg, Germany, 1977). For recent calculations see, for instance, L. L. Chau *et al.*, Phys. Rev. D **27**, 2145 (1983).

[2] E. Fernandez *et al.*, Phy. Rev. Lett. **51**, 1022 (1983).

[3] W. T. Ford, in *Flavor Mixing in Weak Interactions,* Proceedings of the Europhysics Topical Conference, Erice, Italy, edited by L. L. Chau (Plenum, New York, 1984), and Ann. N. Y. Acad. Sci. **461**, 529 (1986).

[4] N. S. Lockyer *et al.*. (MARK II Collaboration), Phys. Rev. Lett. **51**, 1316 (1983); D. E. Klem *et al.* (DELCO Collaboration), Phys. Rev. Lett. **53**, 1873 (1984); W. Bartel *et al.* (JADE Collaboration), DESY Report No. DESY 86-001 (unpublished); M. Althoff *et al.* (TASSO Collaboration), Phys. Lett. **149B**, 524 (1984).

[5] J. Albanese *et al.* (CERN WA75 Collaboration), Phys. Lett. **158B**, 186 (1985).

[6] See, for instance, E. Fernandez *et al.*, Phys. Rev. D **31**, 1537 (1985).

[7] E. Fernandez *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-3390, 1984 (unpublished). A more complete report is in preparation.

[8] E. Fernandez *et al.*, Phys. Rev. D **31**, 1537 (1985).

[9] E. Farhi, Phys. Rev. Lett. **39**, 1587 (1977).

[10] See, for example, E. Fernandez *et al.*, Phys. Rev. Lett. **50**, 2054 (1983).

[11] W. T. Eadie *et al.*, *Statistical Methods in Experimental Physics* (American Elsevier, New York, 1971).

[12] Generator of $e^+e^- \rightarrow q\bar{q}(\gamma)$, F. Berends, R. Kleiss, and S. Jadach, Nucl. Phys. **B202**, 63 (1982); hadronization, B. Andersson *et al.*, Phys. Rep. **97**, 31 (1983) (Lund JETSET version 5.2 code); electromagnetic shower simulation, R. Ford and W. Nelson, Stanford Linear Accelerator Center Report No. SLAC-210, 1978 (unpublished) (EGS code); hadronic shower simulation, T. W. Armstrong, in *Computer Techniques in Radiation Dosimetry,* edited by W. R. Nelson and T. M. Jenkins (Plenum, New York, 1980) (HETC code).

[13] C. Peterson, D. Schlatter, I. Schmitt, and P. M. Zerwas, Phys. Rev. D **27**, 105 (1983).

[14] MAC Collaboration, to be published; D. M. Ritson, in Proceedings of the Twenty-Third International Conference on High Energy Physics, Berkeley, California, 16–23 July, 1986, edited by S. Loken (World Scientific, Singapore, to be published).

[15] E. H. Thorndike, in *Proceedings of the 1985 International Symposium on Lepton and Photon Interactions at High Energy, Kyoto, Japan, 1985,* edited by M. Konuma and K. Takahashi (Kyoto Univ. Press, Kyoto, Japan, 1986).

[16] This value and error result from our own analysis of world data. See E. H. Thorndike, Annu. Rev. Nucl. Sci. **35**, 195 (1985); S. Bethke, Z. Phys. C **29**, 175 (1985).