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Measurement of the B Hadron Lifetime*

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ABSTRACT

Data from e^+e^- collisions collected by the MAC detector at the SLAC storage ring PEP with a new vertex chamber having position resolution of $50\,\mu$m have been analyzed with a new method to make a determination of the lifetime of hadrons containing b-quarks. In addition, data collected with MAC before the vertex chamber was installed have been re-analyzed using the new method. The combined result for the B lifetime is τ_b=$(1.16\pm0.16(stat.)\pm0.07(syst.)\,\mathrm{ps})\times(1\pm0.15)$, where the last factor is the scale.

The fact that the mean lifetime of b flavored 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 these fundamental parameters has led detector groups at e^+e^- colliders to measure lifetimes and branching ratios. Results from PEP and PETRA for the B lifetime range from 0.8 to 1.8 ps.[2] A recently observed event from the CERN WA75 triggered emulsion experiment provides evidence for a B lifetime $\sim$0.3 ps.[3] The installation of a high precision vertex chamber with small inner diameter in the MAC detector at PEP has made improved measurements 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.[4] Only a brief discussion of the components important to this measurement is given here. Fig. 1 shows the tracking devices projected onto the plane transverse to the beam. The central detector (CD) is a ten layer drift chamber in a solenoidal magnetic field of 5.7 kG, with six layers at an angle of 3° to the beam axis, and with the first and last layers at radii of 12 and 45 cm respectively. The average position resolution of a single wire is 160 μm. Fig. 1 also shows the location of the vertex chamber (VC), which was installed in 1984, and has been described elsewhere.[5] Space was created for the VC by reducing the radius of the beam pipe from 8.8 cm to 3.6 cm. Despite the proximity of the beam–pipe to the beam, only two excess background hits per beam–crossing were observed on average in the VC. The VC is composed 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 atmospheres. Each drift tube provides an average position resolution of 50μm. The resolution in the distance of closest approach to the beam centroid in the plane transverse to the beam is 350μm for data prior to VC installation, and 90μm with VC operational, as measured with 14.5 GeV Bhabha events. Multiple scattering in the beam pipe and chamber wall contributes 360μm/p(GeV) and 65μm/p(GeV) respectively to these resolutions.

The barrel calorimetry of MAC has an electromagnetic detector of lead interspersed with proportional wire chambers, for a total of 16 radiation lengths. The hadronic barrel calorimetry and endcap detectors are constructed of alternating layers of steel and gas proportional tubes such that normally incident particles traverse ~ 90 cm of steel corresponding to ~5 nuclear interaction lengths. The calorimetry covers 98% of the full solid angle. The small inner diameter of the calorimeter minimizes the path length available for decay in flight 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 layers of 10 cm diameter drift tubes that measure the exit polar angles of muons traversing the steel, and consequently their momentum, to ~25%.

The parent data samples for the analysis were accumulated at $\sqrt{s} = 29$GeV and consisted of an integrated luminosity of 220 pb^{-1} collected without the vertex chamber, and 94 pb^{-1} from the PEP 1984–86 data cycle with the VC installed. The analysis consisted of first selecting a sample of hadronic events enriched in B-hadron decays by detecting 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 was approximated by the weighted average of the beam centroid, as found from Bhabha events, and information from high quality tracks. The impact–parameter, the distance of closest approach of selected tracks to this average vertex in the plane transverse to the beam, was measured and given a sign. A positive impact–parameter indicates a forward and non-zero 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 were used in the present analysis.

B hadron candidates with a muon or electron having momentum greater than 2 GeV/c were selected from the single photon annihilation hadronic event sample.[11] For muons, a quality OD track was required to link to a clean set of hits in the outer layers of calorimetry. The combined OD and calorimeter information was then required to match a CD track to better than 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 was required, as well as no appreciable energy deposition in the hadronic calorimeter. Further, the shower transverse and longitudinal energy deposition was required to be consistent with an electromagnetic shower.(E. Fernandez *et al.*[2])

Events were then selected according to thrust information,[7] calculated from the calorimeter energy flow information. For events containing muons a correction from tracking information was made to compensate for the energy of the muon not deposited in the calorimeters. The thrust axis was required to be greater than 30° from the beam direction, and the thrust itself required to exceed 0.72 to ensure that the axis was well defined. Events were required to contain a lepton with momentum transverse to the thrust axis of greater than 1.5 GeV/c, a requirement known to provide enrichment in events from $b\bar{b}$ production.[6] Electrons were further required to have momentum components perpendicular to the thrust axis in the plane transverse to the beam direction of greater than 1.2 GeV/c to eliminate a few two photon annihilation events. The data samples were scanned to remove a small number of events arising from cosmic–rays and two–photon processes. The preceding requirements selected 336 muon and 74 electron 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 or estimate the B production point were required to have momentum greater than 0.5 GeV/c and at least seven track linked hits in the CD. For data taken with the VC, at least three linked hits were required in the VC. Tracks used to find the average vertex were 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 were taken from the covariance matrix of the fit procedure, while the weight of the beam was determined from its spatial standard deviation measured in Bhabha events, 70 microns vertically and 350 microns horizontally. Tracks providing impact–parameters were required to be separated from the thrust axis by an angle greater than (0.2 rad)/sinθ_t in the plane transverse to the beam, where θ_t is the angle of the thrust axis relative to the beam. This requirement reduces sensitivity to errors in thrust axis and eliminates tracks containing little information about the B hadron path length. The average vertex was computed omitting the track for which the impact–parameter was being measured. Tracks with impact–parameters greater than 4 mm in the data taken prior to the VC installation and greater than 3 mm in the subsequent data were 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.

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

To provide a statistically robust and precise measure of the impact–parameter distribution the trimmed mean was used as the estimator.[8] The trimmed mean, X, is defined as the mean of a distribution from which fractions f of the tails have been removed symmetrically. The best precision for the experimental impact–parameter distributions was obtained with $f = 0.1$. The statistical error of the trimmed mean was determined from the sample distribution. The lepton tagged data collected prior to VC installation yield a trimmed mean of $154 \pm 20\,\mu$m, and later data give $129 \pm 14\,\mu$m.

B lifetimes were determined by finding the value required by the Monte

Carlo simulation to produce trimmed means equal to those in the data. The Monte Carlo model[9] used for the hadronization simulation was the LUND code with the string option and heavy quark fragmentation functions as given by Peterson *et al.*[10] The model was modified to incorporate initial state QED and weak radiative corrections, secondary decay vertices from unstable particles, and QCD matrix elements to $O(\alpha_s^2)$. For heavy quark events the parameters ϵ_c and ϵ_b were taken to be 0.063 and 0.012 respectively. The default lifetimes used in the Monte Carlo were $\tau_b = 1.2$ ps and $\tau_{D^0} = 0.44$ ps, $\tau_{D^+} = 0.85$ ps, $\tau_{\Lambda_c} = 0.23$ ps and $\tau_{F^+} = 0.19$ ps. The Monte Carlo predicted that 70% of the tracks in the lepton tagged samples came 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 $X_b \approx 180\,\mu\text{m}$, $X_c \approx 25\,\mu\text{m}$, and $X_{uds} \approx 10\,\mu\text{m}$.

The B lifetime determined from the data accumulated prior to VC installation is $\tau_b = 1.14 \pm 0.20(stat.)$ps. Data collected with the VC gives $\tau_b = 1.20 \pm 0.24(stat.)$ ps. The complete electron sample yields $\tau_b = 0.97 \pm 0.29(stat.)$ps, while the muon sample yields $\tau_b = 1.25 \pm 0.19(stat.)$ ps. The combined result is $\tau_b = 1.16 \pm 0.16(stat.)$ ps.

Measurement systematic errors have been studied in five ways. First, impact-parameters of the lepton tagged sample as well as a large control sample of untagged multihadrons were given signs without reference to the thrust axis. The resulting trimmed means were consistent with zero. Second, using the same technique the τ lifetime has been measured: 5,300 τ decays accumulated after VC installation yielded a lifetime of $0.284 \pm 0.016(stat.)$ ps, to be compared with the current world average of 0.280 ± 0.020 ps. The remaining three tests rely on the ability of the MAC Monte Carlo to model detector performance, which has been checked in numerous studies during the past five years. By setting all lifetimes to zero in the Monte Carlo simulation it was verified that the reconstructed impact–parameter distribution was not offset and was symmetric. Comparisons of trimmed means between the control sample and Monte Carlo generated multihadrons agreed to within 10 μm for variations of the impact–parameter cut from 1 to 10 mm and of the trim from 0.0 to 0.5. Finally, the average vertex was replaced by the beam centroid in both data and Monte Carlo. The measurement systematic error estimated from these studies is an additive error of 0.05 ps and a multiplicative error of $\pm 7\%$. The smallness of this additive systematic error is characteristic of the impact–parameter technique.

Expressing the trimmed mean, X, as $f_b X_b + f_c X_c + f_{uds} X_{uds}$, systematic errors due to model dependence of fragmentation are contributed dominantly through the term $f_b X_b$. 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 arose from uncertainty in B fragmentation. Variation of the mean fraction of beam energy retained by the B hadron, corrected for initial state radiation, over the interval 0.73 to 0.83 indicated an error in X_b, multiplicative in τ_b, of $\pm 10\%$. Uncertainty in f_b arose from the uncertainties in: 1) the mean leptonic branching ratio of B hadrons (taken to be $12 \pm 1\%$,); 2) b- and c-quark fragmentation; and 3) detector efficiency. The total $f - b$ systematic uncertainty contribution is $\pm 7\%$. Sensitivity of X_b to lifetimes of particles containing c-quarks is small, because tracks from the sequential decay contribute with both signs to the net impact–

parameter. Uncertainties in D, F, and Λ_c lifetimes contribute a 0.05 ps systematic error. Adding all systematic errors in quadrature gives an error additive in τ_b of ±0.07 ps and a multiplicative error of $\pm15\%$.

The combined value for the B lifetime, based on the results given above, is $\tau_b = 1.16 \pm 0.16(stat.) \pm 0.07(syst.)$ ps, with a systematic multiplicative uncertainty of $\pm15\%$.[12] This value is in agreement with the world average[12] from PEP and PETRA detectors $\tau_b = 1.26 \pm 0.16$ ps, where statistical and systematic errors have been combined in quadrature.

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FIGURE CAPTIONS

1. Layout of the central tracking chamber and vertex detector relative to the beam pipe, shielding and active BGO shielding.
2. Impact–parameter distributions for (a) untagged multi–hadron 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, parameters measured relative to beam center, (e) lepton tagged data before installation of the VC and measured relative to the average vertex, (f) similar data after VC installation. (a)-(d), vertical scale in thousands.

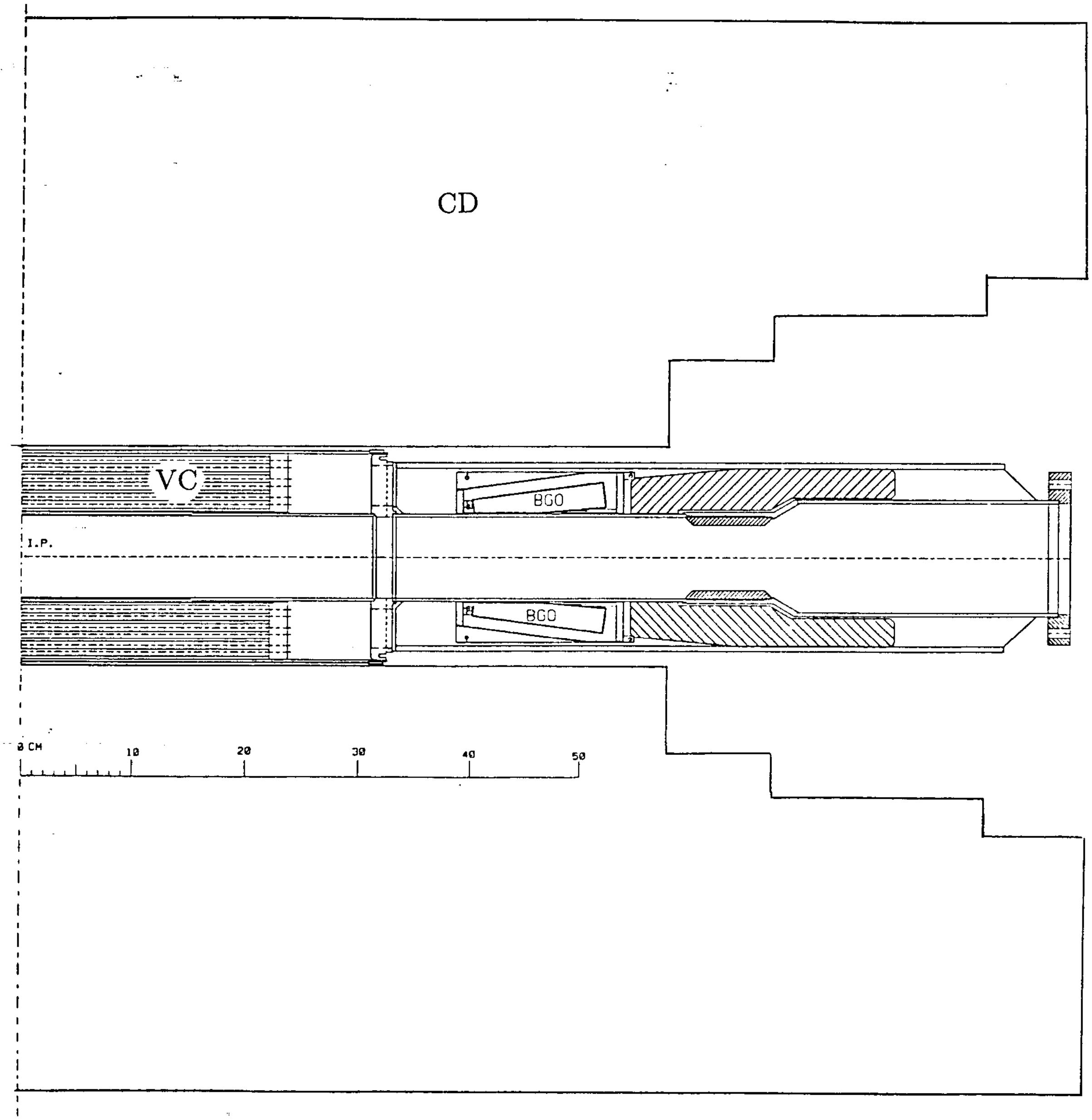
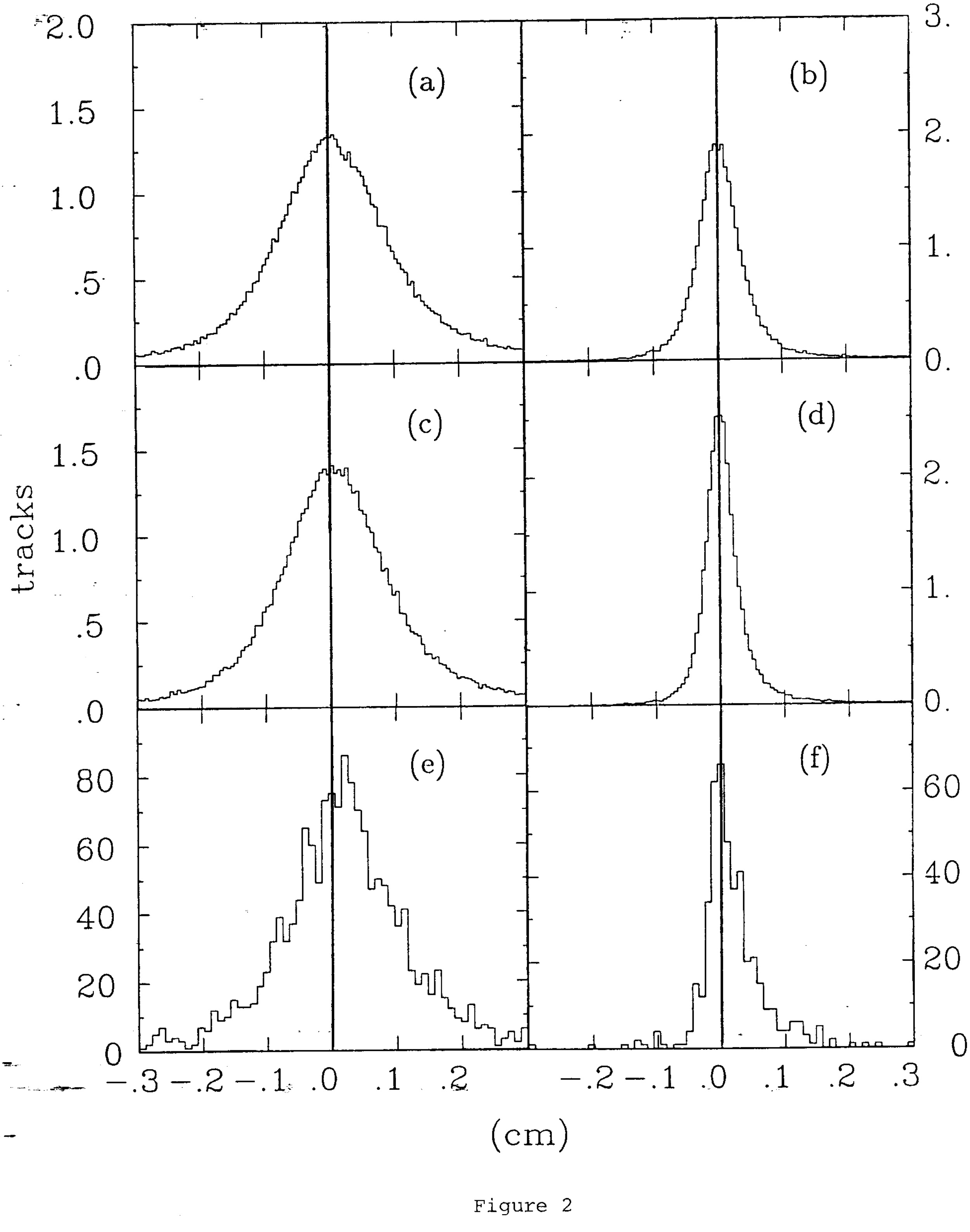


Figure 1



2.0
1.5
1.0
.5
.0
3.
2.
1.
0.
(a)
(b)
(c)
(d)
(e)
(f)
tracks
80
60
40
20
0
60
40
20
0
-.3 -.2 -.1 .0 .1 .2
-.2 -.1 .0 .1 .2 .3
(cm)

Figure 2