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A MEASUREMENT OF THE AVERAGE B HADRON LIFETIME*

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ABSTRACT

Results are reported from a study of the impact parameters of electrons in hadronic events produced at the PEP e^+e^- storage ring. Electrons in hadronic events are produced by bottom and charm decay and their impact parameters show hadrons containing bottom quarks to have a lifetime of $1.16^{+0.37}_{-0.34}(stat) \pm 0.23(sys)$ psec. This result is used to constrain elements of the Kobayashi-Maskawa mixing matrix.

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An accepted theoretical understanding of the mechanism which produces the observed quark generations is not at hand. An important clue to this puzzle comes from the measurement of the transitions between the generations. In particular the rates at which these transitions proceed can be interpreted in terms of mixing among the generations under the weak interaction. The Kobayashi-Maskawa matrix provides a phenomenological description.[1] In this context the b quark lifetime provides constraints on the matrix elements, $|V_{bu}|$ and $|V_{bc}|$, describing the transitions between the b quark and the u and c quarks.

The analysis presented here is based on the impact parameter method, [2,3] which uses the prompt electrons from semileptonic decays of charm and bottom hadrons. The major difference between this measurement and the previous measurements is the use of a Čerenkov identified sample of prompt electrons with momenta as low as 1 GeV/c. [4,5] The resulting data have reduced background contamination from misidentification. The lifetime is derived from the impact parameter (δ) , which is the distance of closest approach of the electron to the center of the e^+e^- beams projected onto a plane perpendicular to the beams. The thrust axis of the event is used to approximate the parent hadron direction and the sign of the impact parameter is given by the sign of the apparent decay length. The average impact parameter ($\bar{\delta}$) depends on the momentum (p) and the momentum transverse to the thrust axis (p_t). Figure 1 is a contour plot of $\bar{\delta}$ calculated for the decay electrons from the process $b \rightarrow eX$, assuming an average b lifetime of $\tau_b = 1.0$ psec. [6,7] It shows that the largest values of $\bar{\delta}$ are obtained when p_t becomes an appreciable fraction of p.

DELCO is an open geometry detector emphasizing electron identification over a large solid-angle. [5,8] The main feature is a 36 cell gas Čerenkov counter covering 60% of 4π steradians. The Čerenkov counters in combination with the shower counters provide pion-electron discrimination of better than 1:1000 and high efficiency. The prompt electron sample [4] comes from an integrated luminosity of 118 pb^{-1}, which combines data taken with isobutane or nitrogen filling the Čerenkov counters. The isobutane data (92 pb^{-1}) is limited to $p < 2.5$ GeV/c by the pion threshold in the Čerenkov counters, while the nitrogen data (26 pb^{-1}) is limited to $p < 5.5$ GeV/c. Electrons with momenta less than 1 GeV/c are not used due to limitations from multiple scattering and backgrounds.

Track quality cuts in addition to those used in Ref. 4 have been placed on the prompt electron sample. Tracks are required to have 11 out of 16 hits in the inner detector, small residuals, and no other tracks within 30 milliradians in ϕ. These cuts ensure accurate extrapolation of the track back to the beam crossing point and minimal confusion at the track finding stage. They narrow the impact parameter distributions by 20% and result in a 30% reduction of the data.

The errors contributing to the impact parameter resolution are due to drift chamber resolution, multiple Coulomb scattering, and the finite beam size. The contribution from drift chamber resolution is measured using e^+e^- pairs from Bhabha scattering. The measured distance between two tracks at the beam crossing point implies a contribution to the average error on the impact parameter for a single track of 283 μm from this source. The multiple scattering contribution is calculated from the thickness of the beam pipe and inner drift chamber wall. This material totals 2.9% of a radiation length and contributes 131 μm for a typical 1.5 GeV/c track.

The beam centroid is determined using beam pickup buttons located 4.5 m either side of the beam crossing point. The devices are calibrated using Bhabha events. The beam spot is assumed to be a two dimensional Gaussian. Its horizontal size is measured to be $\sigma_x = 356 \pm 13\ \mu m$[9] and its vertical size is measured to be $\sigma_y = 44 \pm 51\ \mu m$. This introduces an error on the impact parameter which depends on the azimuthal angle ϕ. The horizontal beam size dominates this contribution until the measured track is within $\pm 7^o$ of the horizontal plane. Averaging over the beam spot and all ϕ gives a mean error of 232 μm from this source. This error, the error from the drift chamber resolution, and the error from multiple Coulomb scattering are calculated for individual tracks. The average error on the impact parameter from all sources is 400 μm for a 1.5 GeV/c track.

A b-enriched region is defined by requiring $p_t > 1$ GeV/c, and a c-enriched region is defined by requiring $p_t \leq 1$ GeV/c and $p \geq 1$ GeV/c. The impact parameter distributions for electrons in the b and c regions are shown in Figs. 2(a) and 2(b). The means of these distributions, $\bar{\delta} = 215 \pm 81\ \mu m$ for the b region and $\bar{\delta} = 137 \pm 54\ \mu m$ for the c region, have significant positive offsets which are larger than previous measurements[2,3]. These differences can be attributed to the different kinematic regions covered and the smaller backgrounds in this data. See Table I. [5]

Experimental cross checks have been performed using three different data sets. In each case the track quality cuts were the same as those used in the electron analysis. Non-electron tracks were selected from hadronic events by requiring no signal in the associated Čerenkov counter. In the b region $\bar{\delta} = 40 \pm 8\ \mu m$ and in the c region $\bar{\delta} = 44 \pm 4\ \mu m$. These small positive $\bar{\delta}$'s may be attributed to the inclusion of hadrons and muons from b and c decays. A Monte Carlo calculation using our measured b lifetime gives $20 \pm 9\ \mu m$ and $34 \pm 5\ \mu m$

for the b and c regions respectively. These numbers are consistent with the data.

A large sample of $e^+e^- \rightarrow e^+e^-e^+e^-$ has been analyzed to show that the technique can obtain a zero lifetime for data which have no long lived particles. The "thrust axis" was taken to be in the direction of the sum of the momenta of the tracks. The resulting distribution has $\bar{\delta} = -10 \pm 14\ \mu m$ which is consistent with zero.

A sample of 617 1-3 topology tau lepton events has been analyzed to demonstrate that the method can measure a "known" lifetime. Using both the 1-prong and 3-prong decays, $\bar{\delta} = 68 \pm 17\ \mu m$, corresponding to a tau lifetime of 0.29 ± 0.08 psec. This value is in agreement with other recent tau lifetime measurements.[10]

A maximum likelihood fit has been done using all tracks with $|\delta| < 3$ mm to extract the b quark lifetime from the electron data set. The probability of observing an electron with momentum p, transverse momentum p_t, and impact parameter δ can be expressed as:

$$P(\delta) = f_b P_b(\delta) + f_c P_c(\delta) + f_{bc} P_{bc}(\delta) + f_{bkg} P_{bkg}(\delta),$$

where the subscripts refer to the processes $b \rightarrow eX$, $c \rightarrow eX$, $b \rightarrow c \rightarrow eX$, and background. The f_i's, which vary with p and p_t, are the relative probabilities that the observed electron comes from the indicated process and are computed in bins of p and p_t.[5] The sum of the f_i's is unity. The $P_i(\delta)$'s are the impact parameter distributions for each process.They are calculated by convoluting exact impact parameter distributions, $P_i^{exact}(\delta)$, with a Gaussian on a track by track basis. The width of the Gaussian is equal to the expected error on the impact parameter for that track. The $P_i^{exact}(\delta)$'s for particular values of τ_b and τ_c are computed as functions of p and p_t using the Monte Carlo without resolution effects.[6] The functions $P_b^{exact}(\delta)$ and $P_c^{exact}(\delta)$ can be obtained for arbitrary values of τ_b and τ_c, since they scale in these variables. For the cascade decay, $b \rightarrow c \rightarrow eX$, no scaling is found, but this process contributes less than 10% of the electrons in any bin in p and p_t for $p_t > 1$ GeV/c. $P_{bc}^{exact}(\delta)$ is calculated using the fitted lifetimes for τ_b and τ_c and is iterated until the fit gives a consistent solution.

Figure 3 is a contour plot of the likelihood function for all electrons with $p >$ 1 GeV/c. The most likely values of τ_b and τ_c are $1.33^{+0.39}_{-0.36}$ psec and $0.77^{+0.50}_{-0.42}$ psec respectively. These numbers are seen to be slightly correlated. The measured value of τ_c is consistent with previous measurements.[7]

Fixing the charm particle lifetimes to their measured values [7] reduces the statistical error on τ_b, and fitting only electrons with $p_t > 1$ GeV/c reduces the systematic error due to the uncertainty in the charm lifetimes. This gives a value of $\tau_b = 1.16^{+0.37}_{-0.34}$ psec, which is consistent with previous measurements.[2,3] A Monte Carlo calculation of $\bar{\delta}$ has been done using this value of τ_b. It gives 224 ± 14 μm in the b region and 120 ± 6 μm in the c region in agreement with the data.

Several sources of systematic errors on τ_b have been considered: track selection criteria contribute $< 5\%$, uncertainties in the fragmentation functions contribute $\approx 10\%$, uncertainties in the calculation of the errors on δ contribute $\approx 5\%$, uncertainties in τ_c and in the f_i's contribute negligibly. Combining these errors gives a total systematic error of 20%.

The average lifetime of hadrons containing b quarks is measured to be $\tau_b = 1.16^{+0.37}_{-0.34}(stat) \pm 0.23(sys)$ psec. The bottom hadron lifetime is related to the mixing matrix elements V_{bu} and V_{bc} by:[11]

$$\tau_b^{-1} = \frac{G^2 m_b^5}{192\pi^3}\left(2.75\,|V_{bc}|^2 + 7.69\,|V_{bu}|^2\right),$$

where m_b is the bottom quark mass and G is the weak coupling constant. The measured upper limit on the non-charm branching fractions of b mesons requires $|V_{bu}|\ /\ |V_{bc}| < 0.14$ [12]. Assuming $m_b = 5$ GeV/c^2, the matrix elements are constrained to the range $|V_{bc}| = 0.054^{+0.010}_{-0.007}(stat)$ and $|V_{bu}| < 0.009$. If the systematic and statistical errors on τ_b are added linearly, $|V_{bc}|$ is constrained to be $0.054^{+0.022}_{-0.011}$.

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TABLE I

Summary of the electron data set. Shown is the number of events in the b and c regions defined in the text and the estimated fractions from each of four sources.

	data	$b \rightarrow eX$	$c \rightarrow eX$	$b \rightarrow c \rightarrow eX$	*Bkg*
b region	60	0.77	0.11	0.06	0.06
c region	128	0.16	0.49	0.16	0.19

FIGURE CAPTIONS

1. Calculated contours of constant $\bar{\delta}$ in the p and p_t plane for electrons from b decays. For $p_t \approx p$ errors are made in assigning the electron to the proper jet and $\bar{\delta}$ becomes small. For small p and p_t, $\bar{\delta} < 0$ can result from electrons produced backward in the rest frame of the parent hadron.
2. The histograms are impact parameter distributions for a) electrons in the b region, and b) electrons in the c region. The smooth curves are the result of a Monte Carlo calculation using $\tau_b = 1.16$ psec and the measured value of τ_c.[7]
3. Contour plot of the likelihood function vs. bottom and charm lifetimes. Contours are drawn at the 1, 2, and 3 sigma levels.

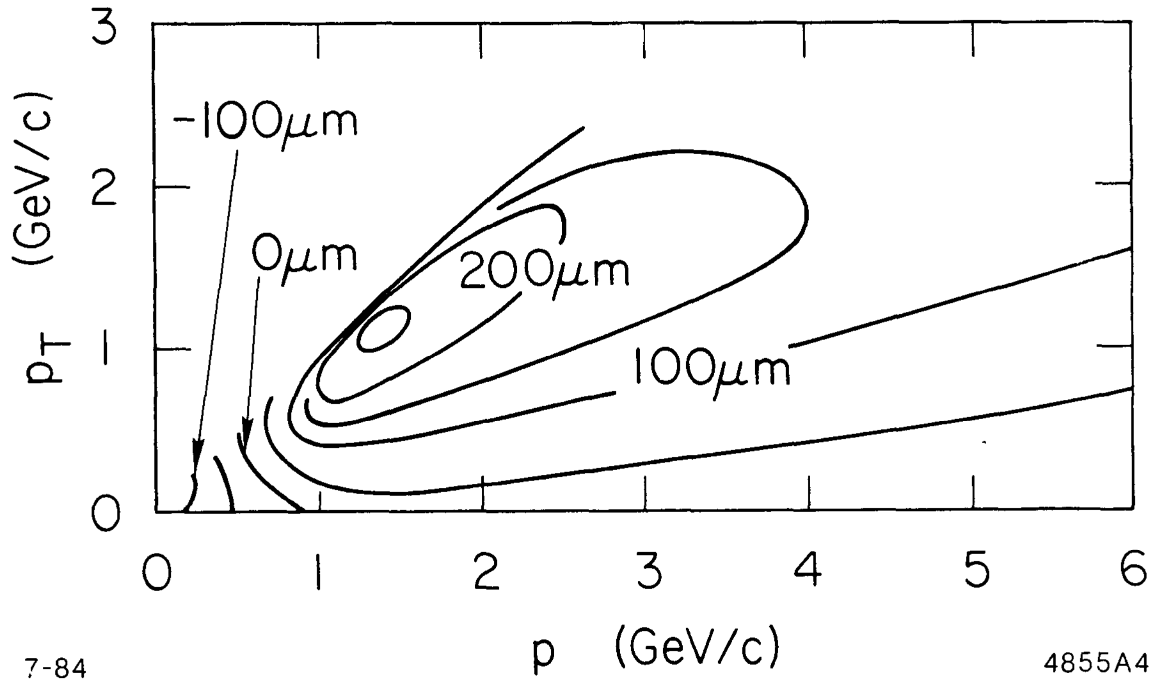
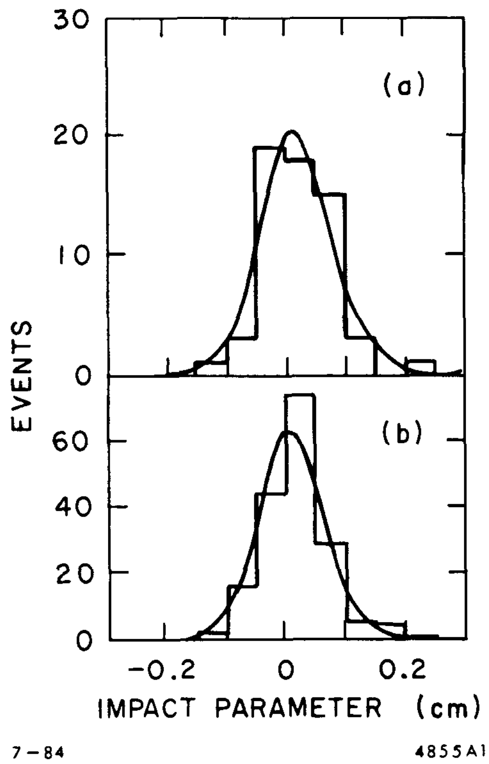


Fig. 1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(a)
20
10
EVENTS
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60
(b)
40
20
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0
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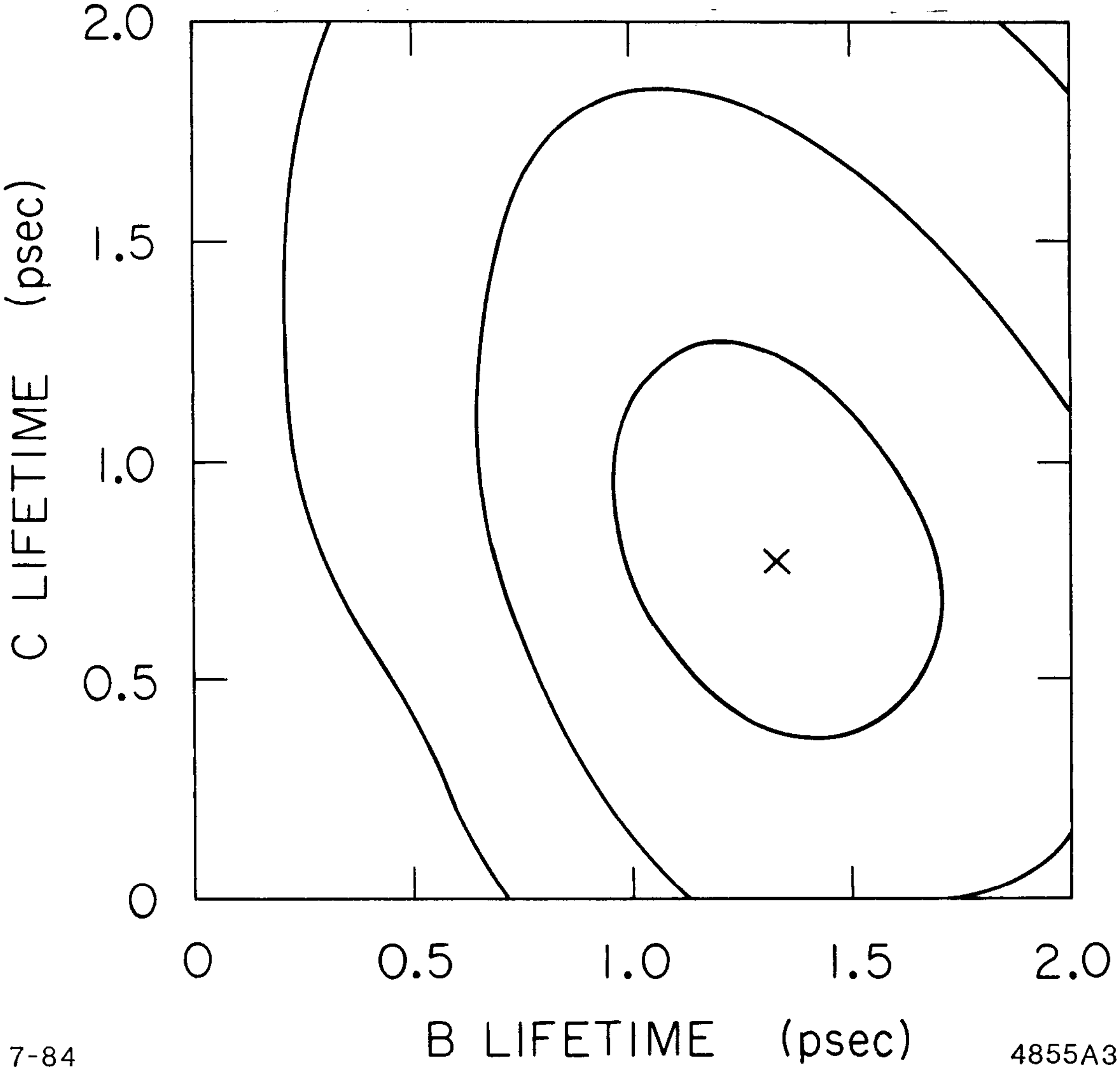
IMPACT PARAMETER (cm)
7-84
4855A1

Fig. 2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1.5
2.0
B LIFETIME (psec)
7-84
4855A3

Fig. 3