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MEASUREMENT OF THE LIFETIME OF BOTTOM HADRONS*

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ABSTRACT

We have measured the average lifetime of bottom hadrons using the Mark II Vertex Detector at PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. We find $\tau_b=(12.0^{+4.5}_{-3.6}\pm 3.0)\times 10^{-13}$ sec.

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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 x 3 quark mixing matrix introduced by Kobayashi and Maskawa (K-M) [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_{cm} 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 chamber [3] (called the vertex detector) is located inside the main tracking chamber. Tracks are extrapolated back to the origin with a resolution of about 100 μ . 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 .25 E_{cm} 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 $p_T < 1$ GeV/c and $p > 3$ GeV/c comprise the charm- enriched sample; those with $p_T > 1$ Gev/c and $p > 2$ GeV/c, the bottom-enriched sample.In this analysis, the thrust direction is determined using all charged tracks in the event. The sine of the angle between the thrust direction and the beam directon 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 analysis [5] of the lepton p and p_T distributions, we find $80 \pm 8\%$ 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 two hour run, we measure the beam position to within 20 μ vertically and 50 μ horizontally. We measure the *rms* beam size to be $65 \pm 15\mu$ vertically and $480 \pm 10\mu$ horizontally.

We ensure that the lepton trajectory is accurately measured by requiring a good track fit ($\chi^2/dof < 4$) 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 μ to 490 μ depending on the azimuthal angle of the lepton. We require that the error be less than 350 μ which leaves 307 leptons for the remaining analysis.

The measured lepton impact parameter distributions are shown in Fig. 1a and 1b for the b-enriched and c-enriched samples, respectively. Including only those tracks which have $|\delta| < 1$ mm, the mean of the b-enriched plot is $106 \pm 29\mu$ and of the c-enriched plot is $63 \pm 18\mu$. The dominant background for both electrons and muons is misidentified hadrons. Accordingly we have measured the impact parameter distribution for non-leptons, weighting the sample over the 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) preceeds the tracking chambers. The impact parameter distribution for the pion and kaon decay background is similar to that for non-leptons. The impact parameter distribution for non-leptons in the b-region is shown in Fig. 1c. The distribution for the c-enriched sample is similar. The average impact parameter in the b-enriched region is $36 \pm 12\mu$ and in the c-enriched region, it is $12 \pm 7\mu$.

The measured impact parameters are fit 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 the 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 distribution 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 fragmentation functions determined 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 $135\mu/10^{-12}$sec in the b-region and $70\mu/10^{-12}$sec in the c-region; for charm decays it is about $120\mu/10^{-12}$sec in the b-region and $95\mu/10^{-12}$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 $|\delta| < 1mm$, is summarized in Fig. 2 which shows equal likelihood contours in the $\tau_c - \tau_b$ plane. The plot shows substantial correlation between the two lifetimes. From this analysis alone we derive for the two lifetimes $\tau_b = (10.3^{+5.2}_{-4.2}) \times 10^{-13}$sec and $\tau_c = (8.3^{+5.1}_{-4.8}) \times 10^{-13}$sec. We can however obtain a more precise value of τ_b by using world data [8] 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 $\tau_c = (6.0 \pm 1.5) \times 10^{-13}$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 $\tau_b = (12.0^{+4.5}_{-3.6}) \times 10^{-13}$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 $14 \pm 12\mu$ in the c region, and $37 \pm 24\mu$ 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 $\tau_b = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}$sec. This lifetime represents an average over bottom hadron species, weighted by the product of their respective production cross-sections and semi-leptonic 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 violation and the top quark mass [12] . The bottom hadron lifetime has been related to the K-M matrix elements by Gaillard and Maiani[13] :

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

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 $|U_{bu}|^2 < 0.02\,|U_{bc}|^2$, 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 $|U_{bc}| = 0.053^{+.010}_{-.009}$. 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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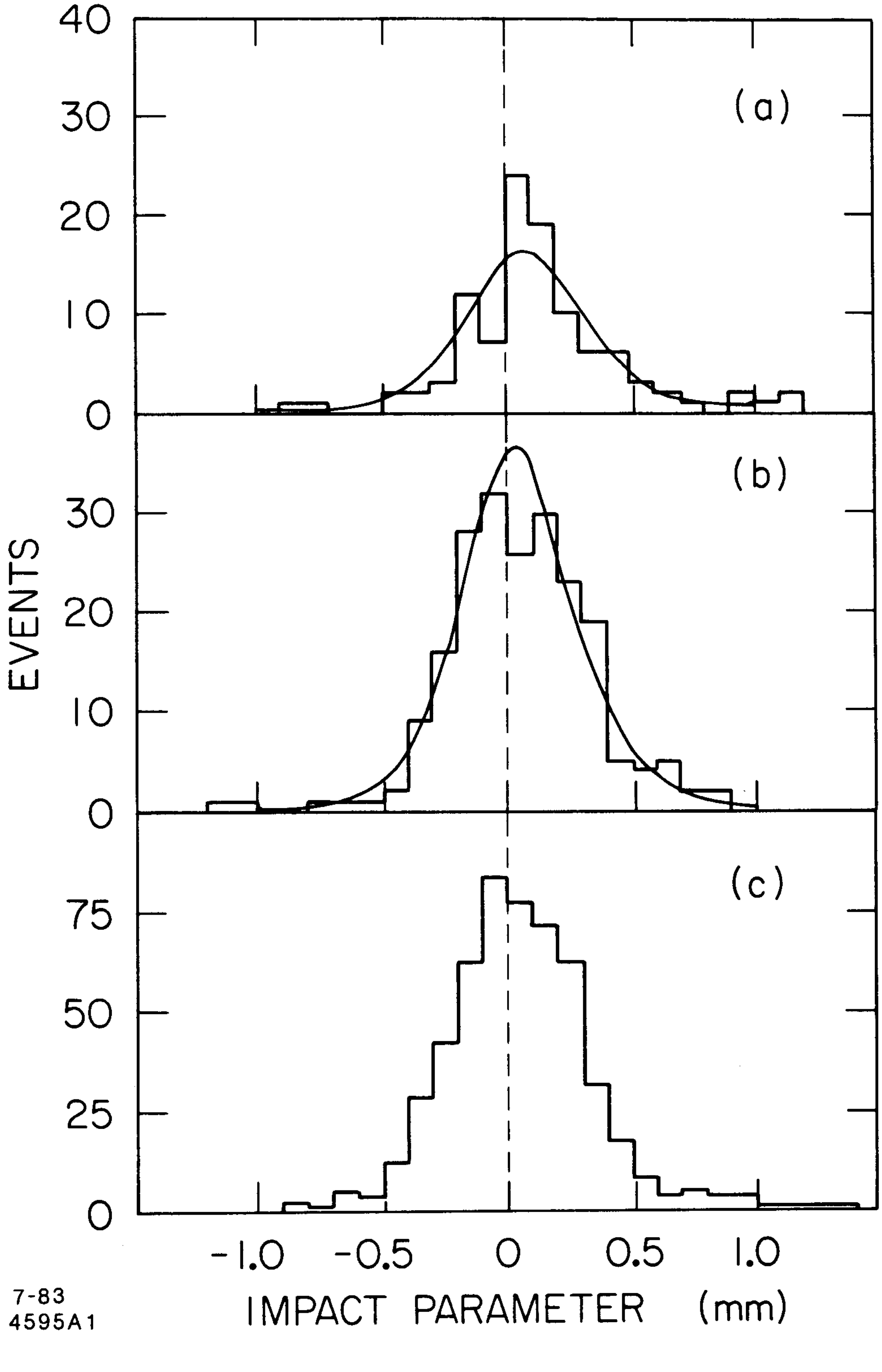
Figures

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



(a)
(b)
(c)
EVENTS
40
30
20
10
0
30
20
10
0
75
50
25
0
-1.0
-0.5
0
0.5
1.0
IMPACT PARAMETER (mm)
7-83
4595A1

Fig. 1

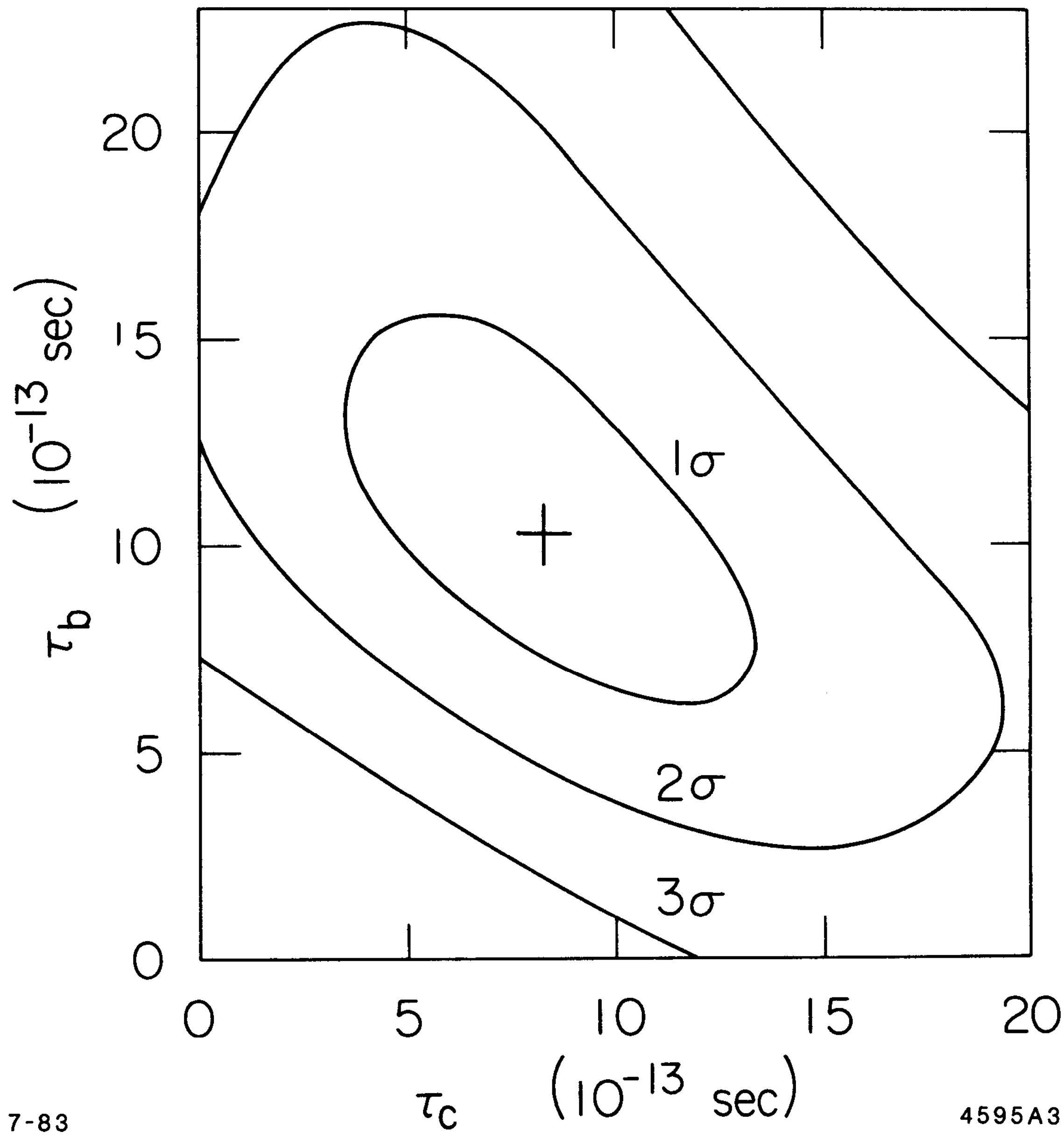

20
15
10
5
0
0
5
10
15
20
τ_b $(10^{-13}$ sec)
τ_c $(10^{-13}$ sec)
1σ
2σ
3σ
7-83
4595A3

Fig. 2