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Measurement of the B^0-Meson Lifetime

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We report a measurement of the lifetime of the B^0 meson based upon 29-GeV e^+e^- annihilation data taken with the Mark II detector at the SLAC storage ring PEP. The B^0 mesons are tagged by their decays into $D^{*-}e^+\nu$ and $D^{*-}\mu^+\nu$, where the D^{*-} is tagged by its decay into $\pi^-\bar{D}^0$. We reconstruct the decay vertices of 15 B^0-meson candidates and measure the B^0 lifetime to be $1.20^{+0.52}_{-0.36}{}^{+0.16}_{-0.14}$ psec.

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While the average lifetime of particles containing b quarks is now reasonably well measured,[1] much less is known about the lifetimes of the individual B mesons and baryons. Recent measurements of exclusive B semileptonic branching ratios have been used[2,3] to constrain τ_{B^0}/τ_{B^+}, but this relies on the assumption that the B^0 and B^+ semileptonic widths are equal. The ratio τ_{B^0}/τ_{B^+} is of interest as it constrains models of the decays of mesons containing heavy quarks.[4] Measurements of τ_{B^0} help refine determinations of the Kobayashi-Maskawa matrix element[5,6] $|V_{cb}|$ and extract information about mixing and CP violation involving B^0 mesons.[7] For these reasons, it is important to have direct measurements of τ_{B^0}.

In this Letter, we report a measurement of τ_{B^0} from 232 pb^{-1} of 29-GeV e^+e^- annihilation data recorded with the Mark II detector at the SLAC storage ring PEP. The detector, in its various configurations, and the multihadronic event selection criteria have been described in detail elsewhere.[8-10] The parts of the detector most important for this analysis are the central drift chamber (CDC), the high-precision vertex drift chamber (VDC) located between the beam pipe and the CDC, the liquid-argon electromagnetic calorimeter, and the muon-chamber system. The CDC, used for charged-particle tracking, and VDC, used for the accurate location of decay vertices, were completely different for the two configurations of the Mark II detector (PEP5 and Upgrade). However, the two configurations have very similar vertex reconstruction capabilities. The impact-parameter resolution for tracks in Bhabha-scattering events is 83 μm for the PEP5 detector and 78 μm for the Upgrade detector. Both detectors have been used to measure heavy-particle lifetimes.[1,10-12]

The B^0 mesons were identified by their decays to opposite-sign $D^{*-}l^+$ pairs.[13] Since the method, described below, for selecting these B decays does not depend upon the complete reconstruction of the decay, we do not directly establish the charge state of each B-meson candidate. However, measured branching ratios for $B^0 \to D^{*-}l^+\nu$ and $B \to D^{*-}l^+\nu X$, where X represents one or more additional pions, can be used to estimate the fraction of $D^{*-}l^+$ pairs coming from B^0 decays rather than B^+ decays. As will be described later, we estimate that approximately 93% of the *real* $D^{*-}l^+$ pairs in our final sample come from B^0 decays.

The $D^{*-}l^+$ pairs were selected by first requiring an identified lepton[14] with momentum transverse to the thrust axis $p_\perp > 1.0$ GeV/c, and total momentum $p > 1$ GeV/c for electrons and $p > 2$ GeV/c for muons. We tried all other tracks in the lepton's thrust hemisphere with $0.1 < p < 1.0$ GeV/c as candidates for the bachelor pion from $D^{*-} \to \pi^- \bar{D}^0$ decay. Instead of trying to reconstruct exclusive $\bar{D}^0$ final states, which has very low efficiency, we formed a $\bar{D}^0$ candidate by adding all remaining charged tracks in the lepton's thrust hemisphere with momentum parallel to the thrust axis $p_\parallel > 0.5$ GeV/c and all photons with $p_\parallel > 1.0$ GeV/c. These cuts exclude most fragmentation tracks. We required that only two or four charged tracks and zero to four photons comprise the $\bar{D}^0$ candidate and that its net charge be zero. We required that the mass of the $\bar{D}^0$ candidate be between 1.2 and 2.1 GeV/c^2 when all charged tracks were assigned pion masses except for the highest momentum track with charge opposite the bachelor pion, which was assigned a kaon mass. In addition, we required that the mass of the combined lepton, bachelor-pion candidate, and $\bar{D}^0$ candidate be between 3.0 and 5.0 GeV/c^2.

We searched for D^{*-} mesons by calculating the mass difference (Δm) between the partially reconstructed $\bar{D}^0$ candidate and the $\pi^-\bar{D}^0$ combination. Figure 1 shows the Δm distribution for those combinations of tracks for which the bachelor pion has a charge opposite that of the lepton, and the distribution when the bachelor pion has the same charge as the lepton. There is a signal which peaks at $\Delta m = m_{D^{*-}} - m_{\bar{D}^0} = 0.145$ GeV/c^2 in the opposite-sign distribution, where we expect the signal from same-hemisphere $D^{*-}l^+$ pairs to appear. Since we allow $\bar{D}^0$ mesons in a wide mass range, the D^{*-} signal in the Δm plot is not so narrow as it would be if a tighter mass cut was used,[15] but the efficiency for detecting $D^{*-} \to \pi^-\bar{D}^0$ decays is higher (approximately 6%). There is no corresponding peak in the like-sign distribution, which is one measure of the background to our signal. Requiring $\Delta m < 0.170$ GeV/c^2, there are 20 $D^{*\pm}l^{\mp}$ pairs, all from different events, and no $D^{*\pm}l^{\pm}$ pairs. Another background check, in which tracks reflected from the opposite thrust hemisphere were used as bachelor-pion candidates, also failed to reproduce the signal observed in the same-hemisphere, opposite-sign pairs.

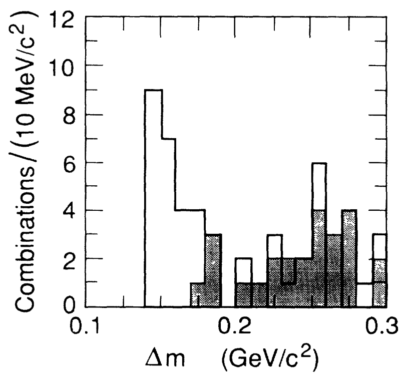

FIG. 1. The Δm distribution for all $\bar{D}^0$-candidate-bachelor-pion combinations for which the bachelor pion has charge opposite that of the high-$p_\perp$ lepton in the same thrust hemisphere (solid line), and for which the bachelor pion has the same charge as the lepton (hatched area).

We studied our cuts with a Monte Carlo calculation which used the Lund JET−SET 6.3 program[16] to generate multihadronic e^+e^- annihilations. These events were passed through our detector-simulation programs, and finally reconstructed and analyzed with the same programs used for the data. After all cuts that define the $D^{*-}l^+$ sample, these studies predicted that we should observe 16 ± 1.5 $D^{*\pm}l^{\mp}$ pairs, $(87 \pm 3)\%$ of which come from B^0 decay, and 2 ± 0.5 $D^{*\pm}l^{\pm}$ pairs. The $\bar{D}^0$ mesons found in the Monte Carlo sample contain 89% of their charged decay products and 38% of their neutral decay products.

Track-quality cuts were imposed on the lepton and at least two tracks from the $\bar{D}^0$ to insure that decay lengths were accurately measured. We required that each track be measured by at least three layers of the VDC. We used only these tracks to determine the B^0 and $\bar{D}^0$ decay vertices, and we required that each track used in the vertex fits, plus the bachelor pion, not come from a K^0 decay or a photon conversion.[17] Three of the twenty pairs failed these requirements. The events were then visually scanned to reject tracks with obvious hit association problems in the VDC, and tracks from missed photon conversions. Two events were rejected by this scan because the track identified as the bachelor pion came from a clear photon conversion outside the VDC, with no associated hits in the VDC.

The tracks from the $D^{*-}l^+$ pairs in the Monte Carlo events were subjected to the same requirements and visual scan as the data before each event's identity as signal or background was ascertained. Of the B^0 decays in

Monte Carlo events, 95% had all tracks used in the vertex fits assigned to the correct vertex.

For the final sample of 15 $D^{*-}l^+$ pairs, we determined the lifetime of the parent particle. In the plane transverse to the beam, we formed a vertex of all tracks which passed the above cuts and came from the $\bar{D}^0$ candidate. Using the direction of the partially reconstructed $\bar{D}^0$, and the position and associated error matrix of this vertex, we extrapolated the $\bar{D}^0$ to form a vertex with the lepton. Since the low-momentum bachelor pion has a large probability of being significantly scattered in the beam pipe and associated material, it was not used in the fit for this vertex. We used the position and error matrix of the $\bar{D}^0 l^+$ vertex (our measurement of the B^0 decay position), the location and extent of the beam overlap region, and the $D^{*-}l^+$ direction to calculate the transverse projection of the B^0-meson decay length and its associated error.[11] Each decay length was then multiplied by $K/\gamma\beta c \sin\theta$ to convert it into a proper lifetime, where θ is the angle between the $D^{*-}l^+$ direction and the beam axis, and K is a constant which corrects, on the average, for the fact that we used the measured $\gamma\beta\sin\theta$ of the $D^{*-}l^+$ pair for that of the B^0 meson. We evaluated K with our Monte Carlo calculation to be 1.12 ± 0.02. The lifetime measurements and their errors are shown in Fig. 2(a).

We examined the distribution of the difference between the reconstructed and generated lifetime, divided by the error on the reconstructed lifetime, for all reconstructed B^0 decays in the Monte Carlo sample. If the B^0 and $\bar{D}^0$ were fully reconstructed, this distribution should be a Gaussian centered at zero with unit standard deviation. We found a distribution with a mean consistent with zero and a standard deviation of 1.23 ± 0.12. When the true B^0 and $\bar{D}^0$ directions and $\gamma\beta\sin\theta$ were used in place of the partially reconstructed ones, the standard deviation of the distribution was equal to one within errors. Therefore, we increased the errors on each individual lifetime determination by 25% in the fit for τ_{B^0}.

The fraction of $D^{*-}l^+$ pairs which came from B^0 decays (f_{B^0}) was estimated with measured B semileptonic branching ratios and some reasonable assumptions. We assumed that the reaction $B \to \bar{D}^* l^+ \nu X$ is dominated by $B \to \bar{D}^{**} l^+ \nu$, where the D^{**} decays into $D^*\pi$, and that the branching ratios for B^0 and B^+ decaying into $\bar{D}^{**} l^+ \nu$ are equal. These assumptions and the isospin coefficients for $D^{**} \to D^*\pi$ result in the relationships $B(B^+ \to D^{*-}\pi^+ l^+ \nu) = \frac{2}{3} B(B \to \bar{D}^{**} l^+ \nu)$ and $B(B^0 \to D^{*-}\pi^0 l^+ \nu) = \frac{1}{3} B(B \to \bar{D}^{**} l^+ \nu)$. Assuming equal production rates for B^0 and B^+, we derived the relationship

$$1 - f_{B^0} = \frac{2}{3} \left[1 + \frac{\eta B(B^0 \to D^{*-} l^+ \nu)}{\eta' B(B \to \bar{D}^{**} l^+ \nu)} \right]^{-1},$$

where η and η' are the efficiencies for reconstructing the $D^{*-}l^+$ signature from $B^0 \to D^{*-} l^+ \nu$ and $B \to \bar{D}^{**} l^+ \nu$, respectively. With our Monte Carlo programs, we calculated that $\eta/\eta' = 1.75 \pm 0.36$. This ratio is greater than one due to the decreased average p and $p_\perp$ of the lepton in the $B^+ \to D^{*-}\pi^+ l^+ \nu$ decay, and due to the additional fast charged pion, which reduces the probability of the $\bar{D}^0$ and D^{*-} candidates passing the total charge, mass, and Δm requirements. Averaging together results from CLEO (Ref. 18) and ARGUS (Refs. 3, 19, and 20), we have calculated that $B(B^0 \to D^{*-} l^+ \nu) = (4.9 \pm 0.4)\%$ and that $B(B \to \bar{D}^{**} l^+ \nu) = (1.0 \pm 1.2)\%$, where the error on the first branching ratio is statistical only.[21] With these values, we estimated that $f_{B^0} = 0.93 \pm 0.08$. After accounting for the background to the D^{*-} signal and for lepton misidentification using Monte Carlo studies, the fraction of $D^{*-}l^+$ candidates which came from B^0 decay was 0.83 ± 0.08.

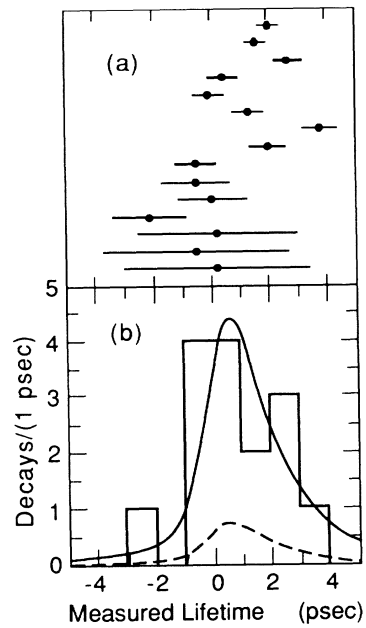

FIG. 2. (a) The fifteen B^0-lifetime measurements and their errors, and (b) a histogram of the measurements with the fitted signal and background curve (solid) and the background curve (dashed) overlaid.

We performed a maximum-likelihood fit of all fifteen proper lifetime measurements to an exponential lifetime distribution convoluted with the measurement errors for the signal, and a similar distribution fixed at 17% of the total signal to account for the background. The functional forms used in this fit are described in Ref. 11. In Monte Carlo samples 2.5 (1.9) times larger than the number of $c\bar{c}$ ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$) events in the data sample, we found no $D^{*-}l^{\pm}$ pairs which passed all the requirements. Therefore, the best estimate of the lifetime of the background distribution is the world-average B-hadron lifetime,[1] 1.18 psec. The lifetime of the signal distribution, the only free parameter in the fit, is found to be

$1.20^{+0.52}_{-0.36}$ psec. The combined signal and background fit (solid line) and the background fit (dotted line) are shown in Fig. 2(b) over a histogram of the fifteen lifetime measurements.

To estimate the systematic error in our measurement, we varied the input parameters to the fit. Since the assumed background lifetime is very similar to the fit lifetime, τ_{B^0} changed very little for large variations of the background fraction. For this reason, we coupled the systematic error estimate of the background fraction with that of the background lifetime. We varied the background lifetime from 0.60 to 2.4 psec with the background fraction set 1 standard deviation higher than our estimate. The fit τ_{B^0} varied from 1.34 to 1.08 psec. We varied the decay-length correction factor K by ± 0.06, and the amount by which we increased the measurement errors from 0% to 50%. To estimate the systematic error from background $D^{*-}l^+$ pairs *not* from B decay (not seen in the Monte Carlo studies), we added a Gaussian function with zero lifetime to the fitting function and allowed it to account for 7% of the observed pairs. We added all these estimates of systematic error together in quadrature for a total of $^{+0.16}_{-0.14}$ psec. As an additional check, we generated Monte Carlo samples of B^0 mesons with lifetimes of 0.6, 1.1, and 1.6 psec, and processed them through the entire analysis chain. The resulting distributions fit to the lifetimes of $0.60^{+0.12}_{-0.10}$, $1.16^{+0.21}_{-0.17}$, and $1.78^{+0.28}_{-0.24}$ psec, respectively.

In conclusion, we have measured the B^0-meson lifetime to be $1.20^{+0.52+0.16}_{-0.36-0.14}$ psec. This measurement, together with the world-average B-hadron lifetime of 1.18 ± 0.12 psec, indicates that the lifetime of the B^0 and B^+ mesons are not grossly different. This is in good agreement with the CLEO and ARGUS measurements of τ_{B^0}/τ_{B^+}. The sources of systematic error in these two analyses are very different.

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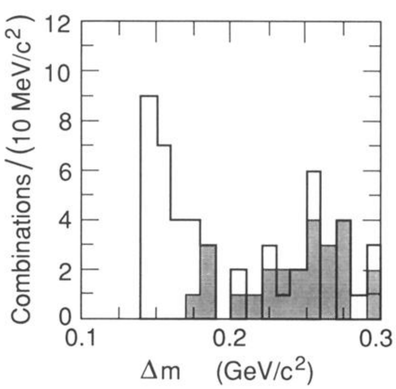

FIG. 1. The Δm distribution for all $\bar{D}^0$-candidate–bachelor-pion combinations for which the bachelor pion has charge opposite that of the high-$p_\perp$ lepton in the same thrust hemisphere (solid line), and for which the bachelor pion has the same charge as the lepton (hatched area).