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Measurement of the D^0 Lifetime from the Upgraded Mark II Detector at PEP*

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ABSTRACT

We present a new measurement of the D^0 meson lifetime based on 31 pb^{-1} of e^+e^- interaction data taken at $\sqrt{s} = 29$ GeV. The data were recorded with the upgraded Mark II detector, which allowed the identification of a clean D^0 signal from this small data set. Using a sample of 53 D^0 candidates based on the decays $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$, we measure the D^0 lifetime to be $0.44^{+0.12}_{-0.11} \pm 0.06$ picoseconds.

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In this paper we report a new measurement of the D^0 meson lifetime, performed with the upgraded Mark II detector[1] at PEP. This analysis is based on 31 pb^{-1} of e^+e^- interaction data taken at $\sqrt{s}$= 29 GeV. The D^0 mesons were tagged by the spectator pion from the $\pi^+ D^0$ decay of the D^{*+}. The same decay length method used to measure the D^0 lifetime in a previous publication of the Mark II collaboration[2] is employed here, but the components of the detector crucial to this analysis have changed completely, and this measurement is statistically independent of the previous one.

The original Mark II detector[3] was upgraded for its planned use at the SLAC Linear Collider (SLC), where the average particle momentum will be higher and the hadronic jet environment denser than at PEP. The PEP run, from which the data presented in this paper is taken, was used to check out the upgraded detector and to take advantage of the many improvements to the detector in the study of physics at PEP energies. The new components used in this analysis are a 72 layer cylindrical main drift chamber[4] (DC), situated in a solenoidal magnet with a nominal field strength of 4.5 kG, and a six layer cylindrical trigger drift chamber[5] (TC), located between the DC and the beam pipe. The layers of the DC are grouped together in twelve "superlayers" each consisting of six layers of wires. The wires in the odd numbered superlayers are parallel to the cylindrical axis and the wires in alternating even numbered superlayers are pitched at +66 mrad and −66 mrad with respect to the cylindrical axis to provide stereo information. The DC has an active length of 2.30 m; the number of sense wires per layer ranges from 26 at the inner radius of 25.0 cm to 136 at the outer radius of 144.4 cm. The TC consists of six layers of axial sense wires in 4 mm radius aluminized mylar tubes. The inner layer of this chamber has 72 wires at a radius of 9.5 cm, and the outer layer has 112 wires at a radius of 14.8 cm. The average point measurement resolution is 175 μm for the DC and 90 μm for the TC. The non-vertex-constrained momentum resolution is $\sigma_p/p^2 = 0.0034$ $(\mathrm{GeV/c})^{-1}$, measured with 14.5 GeV/c electron tracks which traverse all layers of both chambers ($|\cos\theta| < 0.62$) in Bhabha scattering events.

The position resolution of a track extrapolated back to the beam position, in the plane transverse to the beam axis, can be measured from the distribution of separation distances of collinear Bhabha tracks. This resolution, which is the standard deviation of the separation distance distribution divided by $\sqrt{2}$, is $\sigma_{ext} = 78\ \mu\text{m}$ for our detector. We calculate the contribution to this resolution due to multiple scattering in the beam pipe and TC chamber inner wall to be $\sigma_{MS} = 152\ \mu\text{m}/p$ for tracks perpendicular to the beam axis.

The average beam interaction point was derived from Bhabha-scattering events for luminosity subsamples of $\sim 0.5\ \text{pb}^{-1}$. Tracks within ± 52 mrad of the vertical (horizontal) plane were used to measure the size σ_x (σ_y) of the PEP beam-beam overlap. The distributions of impact parameters in the transverse plane, relative to the derived average interaction point, are convolutions of the true beam-beam overlap, the movement of the average interaction point within a measurement period, and the track extrapolation error. For our data, these distributions are well described by Gaussians centered at zero. The effective beam size measured from these distributions, with the track extrapolation error unfolded, is $\sigma_x = 403 \pm 14\ \mu\text{m}$ and $\sigma_y = 52 \pm 11\ \mu\text{m}$.

An event was included in the multihadron data sample used in this analysis if it had at least five charged tracks, a reconstructed primary vertex with a position less than 4 cm in radius and 10 cm in z (distance along the beam axis) from the beam intersection point, more than 25% of the beam energy in charged tracks, and more than 50% of the beam energy in charged tracks and neutral clusters in the calorimeters which surround the DC.[1,3] The charged tracks used to meet the above cuts were each required to have at least 0.1 GeV/c of momentum transverse to the beam, an angle θ with respect to the beam such that $|\cos\theta| < 0.8$, and a distance of closest approach to the beam intersection point of less than 6 cm in radius and 10 cm in z. In addition, if a charged track had a momentum greater than 12.5% of the beam energy, its contribution to the energy sums was limited to this amount.

The method of tagging $D^{*+} \to \pi^+ D^0$ decays[6] with the spectator charged pion has been in use for many years,[7] and is well established. In our analysis, we divided each multihadron event into two hemispheres using a plane perpendicular to the thrust axis determined from charged tracks, and tried every charged track with $p > 0.4$ GeV/c as a spectator pion in association with the D^0 candidates in the same thrust hemisphere. A D^0 candidate was chosen as either: I) a two-track combination with a $K^-\pi^+$ mass between 1810 and 1920 MeV/c^2, II) a two-track combination with $1580 < m_{K^-\pi^+} < 1700$ MeV/c^2, or III) a four-track combination with $1810 < m_{K^-\pi^+\pi^-\pi^+} < 1920$ MeV/c^2. No particle identification was used in our analysis. We tried all possible K and π mass assignments, consistent with the requirement that the kaon has a charge opposite that of the spectator pion, and that the total charge of the D^0 candidate be zero. Cases I and III correspond to fully reconstructed D^0 decays, and Case II corresponds to the satellite resonance of the decay $D^0 \to K^-\pi^+\pi^0$, where only the $K^-\pi^+$ mass is reconstructed. Due to the dynamics of the $D^0 \to K^-\pi^+\pi^0$ decay, a large part of the $K^-\pi^+$ invariant mass distribution is in the mass region of Case II.[8] We required each track from the D^0 candidate to have $p > 1.2$ GeV/c for Case II and $p > 0.8$ GeV/c for Case III. For Case I we required that the helicity angle of the K^- in the D^0 rest frame satisfy $-0.8 < \cos\theta_H < +0.8$, which is nearly equivalent to a 1.0 GeV/c minimum momentum cut on the K^- and π^+ from the D^0 decay. In addition, we required that x, the combined energy of the spectator pion and the D^0 candidate divided by the beam energy, be greater than 0.5. This was done because the D^{*+} signal has less combinatorial background and a smaller contribution from the decay $B \to D^{*+}X$ at $x > 0.5$.[9] The D^{*+} mesons from B meson decay complicate the D^0 lifetime measurement due to the non-negligible B meson lifetime. For Case III there were occasionally more than one D^0 candidates in a thrust hemisphere which satisfied all the above cuts. Since these duplicate combinations generally shared many of the same tracks, in these cases we chose the $K^-\pi^+\pi^-\pi^+$ combination with mass closest to the D^0 mass as the only D^0 candidate in that thrust hemisphere.

We then calculated the difference in mass (Δm) between the spectator pion-D^0 candidate pair and D^0 candidate. The fully reconstructed D^0 decays (Cases I and III) are histogrammed together in Fig. 1a, and show a narrow signal, consistent with our expected resolution, centered near the world average value[10] of $\Delta m = m_{D^{*+}} - m_{D^0} = 145.45$ MeV/c^2. The $D^0 \rightarrow K^-\pi^+\pi^0$ satellite decay produced a broad Δm enhancement between 140 and 152 MeV/c^2 (Fig. 1b). The degraded Δm resolution in Case II is caused by the uncertainty in the D^0 momentum due to the missing π^0. We took our D^{*+} signal for Cases I and III to be all spectator pion-D^0 candidate combinations with $143.5 < \Delta m < 147.5$ MeV/c^2 and, for Case II, those combinations with $\Delta m < 152$ MeV/c^2. The D^0 mesons used for our lifetime measurement were the decay products of these D^{*+} mesons.

In addition to the cuts described above, we required that at least two tracks from the D^0 decay contain four or more TC position measurements (hits), and we used only these tracks in the secondary vertex fit to determine the D^0 decay point and its associated error matrix. For the $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$ decay, this meant that not all tracks from the D^0 decay were required in the vertex fit, though the full information from the D^0 decay was used in all other stages of the analysis. This was done because it was possible for some tracks from the D^0 decay not to have at least four good TC hits because of track overlap, but by the time they traversed the DC, to be cleanly separated and reconstructed, due to the superior angular resolution and multi-hit capability of the DC.

There were 53 D^0 candidates which passed the above requirements and had a vertex fit probability greater than 0.01. We estimate that $17 \pm 7\%$ of these candidates are from random combinatorial background, and $6 \pm 3\%$ are from $B \rightarrow D^{*+}X$ decays. We scanned the events to make sure that none of the tracks included in the D^0 vertex fit had erroneous or ambiguous TC hits associated with them, and to inspect the rest of the event for obvious event selection or track reconstruction errors which would affect the lifetime measurement. None of the D^0 candidates failed these scanning criteria.

The formulae for calculating the most probable path length (in the transverse plane) of the D^0, from its production point to its decay vertex, and the associated error, are given in Ref. 2. These formulae are functions of the vertex position, the beam position, the associated error matrices, and the reconstructed momentum vector of the D^0. The path length was converted into a lifetime by dividing it by the measured $\gamma\beta c \sin\theta_D$, where θ_D is the angle between the D^0 direction and the beam axis. For the $D^0 \to K^-\pi^+\pi^0$ satellite decay, where only the K^- and π^+ tracks are reconstructed, the momentum vector and mass of the $K^-\pi^+$ combination were used. Monte Carlo simulations show this approximation to be a negligible source of error. A histogram of the distribution of lifetime measurements, which has a mean of 0.48 ± 0.11 psec, is shown in Figure 2.

We performed a maximum likelihood fit to the lifetime measurements. The fitting function, which is also described in detail in Ref. 2, was the sum of a decay exponential convoluted with a Gaussian resolution function for the directly produced D^0 mesons in the sample, the same function convoluted with another decay exponential to simulate the $B \to D^0 X$ background, and a Gaussian with its mean offset from zero lifetime to describe the background from random combinations of tracks in multihadron events which pass all of the D^0 selection requirements.

We used a B meson lifetime of 1.16 psec in the background function.[11] The offset of the Gaussian used for the combinatorial background was taken from the weighted-mean lifetime of a side-band sample. This sample consisted of all two- and four-charged-track combinations which passed the same cuts as were applied to tracks in the D^0 signal region, except that we required the combination's invariant mass to be between 2000 and 2400 MeV/c^2. To increase the statistics in this sample, we did not require the total charge of a combination to be zero and did not require a spectator pion with which the combination would pass the Δm cut. This sample should have approximately the same mix of lifetimes as the random combinatorial background in the D^{*+} sample. The weighted-mean of the distribution of side-band lifetimes is 0.19 ± 0.01 psec for the data, and is 0.17 ± 0.01 psec for a Monte Carlo data sample generated with the Lund JETSET

6.3 program[12] and passed though our detector simulation.

The fit to the data gave a D^0 lifetime of $0.44^{+0.12}_{-0.11}$ psec (statistical error only). The contributions to the estimate of the systematic error from the various parameters used in the fit are shown in Table 1. As in Ref. 2, we included a scale factor in our fits to account for systematic mis-assignment of track errors. The scale factor was set to 1.2, based on a comparison of the track error matrices and the measured separation distance distribution for tracks in Bhabha scattering events. Other checks of track resolution in multihadron events, and leaving the scale factor as a free parameter in the fit, gave values for the scale factor well within the amount (± 0.2) by which we varied it to estimate its contribution to the systematic error.

The fraction of random combinations in the D^0 sample was estimated by taking the shape of the Δm distribution for this background from Monte Carlo studies and normalizing it to the Δm regions above the D^{*+} signals in Figures 1a and 1b. The significant positive lifetime of the side-band sample confirms that there are some non-zero lifetime decay products from charm and beauty decays in this background, so we assign a large range of possible values to the Gaussian offset when estimating its contribution to the error. For another check, we generated Monte Carlo samples with the D^0 lifetime set to 0.1, 0.4, and 0.8 psec. We analyzed these samples, which had complete detector simulation, with the same programs as were used for the real data. The measured lifetimes of the D^0 candidates in these samples were consistent with the input lifetimes to within ± 0.03 psec, which we took as the systematic error contribution from any overall lifetime measurement offset.

While the average B meson lifetime is now reasonably well determined, it is possible that the B^0 and B^- lifetimes and their branching ratios to $D^{*+}X$ are significantly different. Because of this, we took the range over which we varied τ_B in our systematic error estimate to ± 0.4 psec. The Monte Carlo estimate of the fraction of D^0 mesons from B decay is likewise dependent on the fragmentation functions used for c and b quarks, the dynamics of the $B \rightarrow D^{\star +} X$ decay, and the above branching ratios. We have adjusted the Monte Carlo parameters to give the good agreement with measured fragmentation functions, B decay multiplicities, and the $D^{\star +}$ momentum spectrum from B decays, and estimate the systematic uncertainty in the fraction of D^0 mesons from B decays in our sample to be ± 0.03.

We have investigated other possible sources of systematic error, such as a rotation of the TC with respect to the DC, and a difference between the real beam spot size and the one used in the decay length calculation, but we find these to be negligible. When added in quadrature, the total estimated systematic error from the contributions in Table 1 is ± 0.06 psec.

In conclusion, we have measured the lifetime of the D^0 meson to be $0.44^{+0.12}_{-0.11} \pm 0.06$ psec. This result is consistent with our previous measurement of the D^0 lifetime and with the current world average,[11] which is dominated by a recent measurement from the Fermilab Tagged Photon Spectrometer collaboration of $0.435 \pm 0.015 \pm 0.010$ psec.[13]

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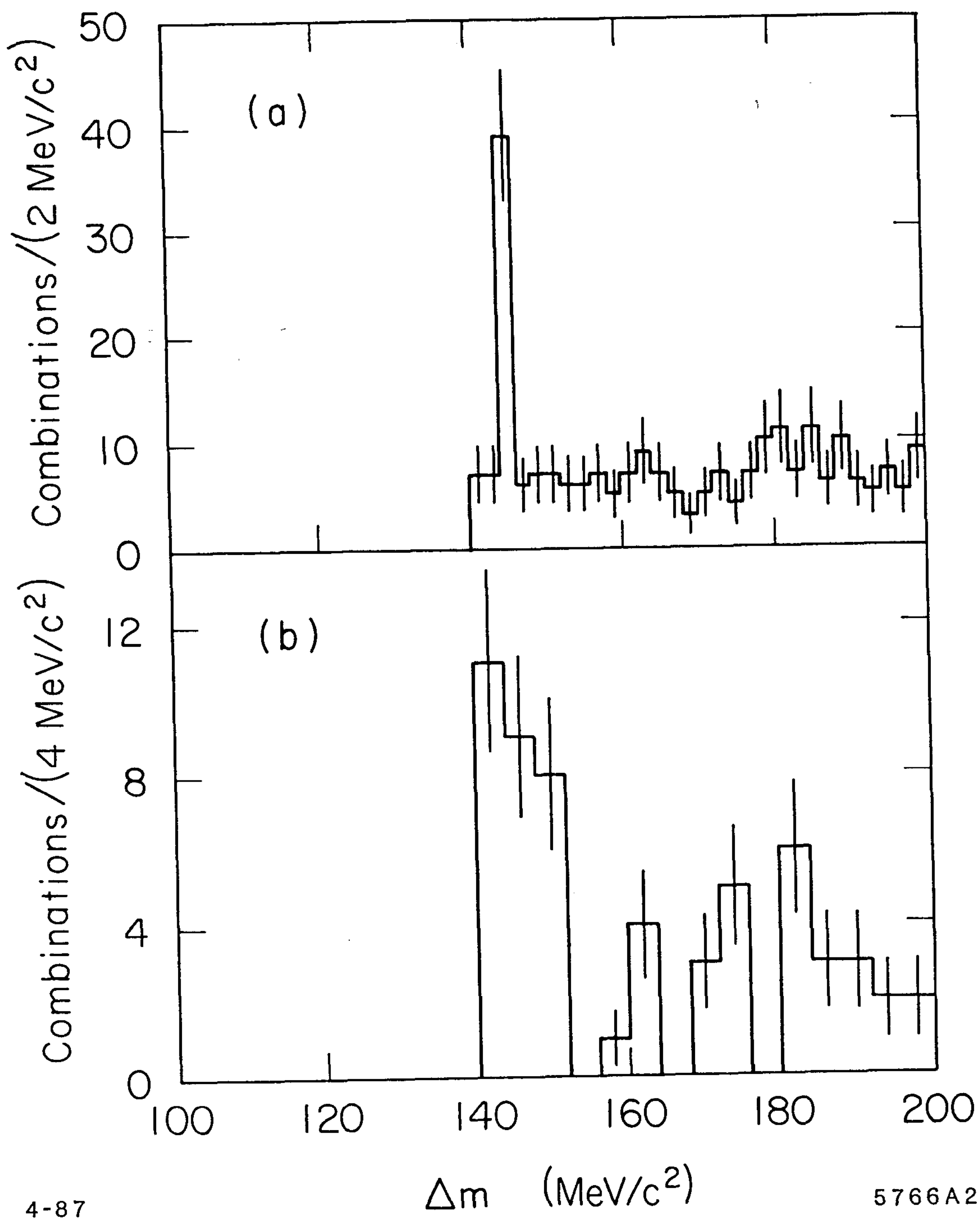
Source of Systematic Error	Estimated Range	Contribution
Resolution scale factor	1.2 ± 0.2	± 0.03 psec
Fraction of signal from random combinations	0.17 ± 0.07	± 0.02 psec
Offset of Gaussian for random combinations	$+0.19$ ± 0.10 psec	± 0.01 psec
Overall measurement offset		± 0.03 psec
Fraction of signal from $B \to D^0 X$	0.06 ± 0.03	± 0.03 psec
Average B lifetime for $B \to D^0 X$	1.16 ± 0.40 psec	± 0.01 psec

Table 1. Contributions to estimated systematic error.

FIGURE CAPTIONS

1. The Δm distribution for all D^0 candidate-spectator pion combinations, as described in the text, where (a) the D^0 candidate is a fully reconstructed $K^-\pi^+$ or $K^-\pi^+\pi^-\pi^+$ decay, and (b) the D^0 candidate is in the satellite region, corresponding to the high mass $K^-\pi^+$ reflection of the $D^0 \to K^-\pi^+\pi^0$ decay.

2. The distribution of measured D^0 lifetimes. The solid curve is the full fit of the signal and background functions, the dotted curve is the contribution to the fit of random combinatorial background, and the dashed curve is the contribution from $B \to D^0 X$ background.



(a)
(b)
Combinations/(2 MeV/c²)
Combinations/(4 MeV/c²)
0
10
20
30
40
50
0
4
8
12
100
120
140
160
180
200
Δm (MeV/c²)
4-87
5766A2

Figure 1.

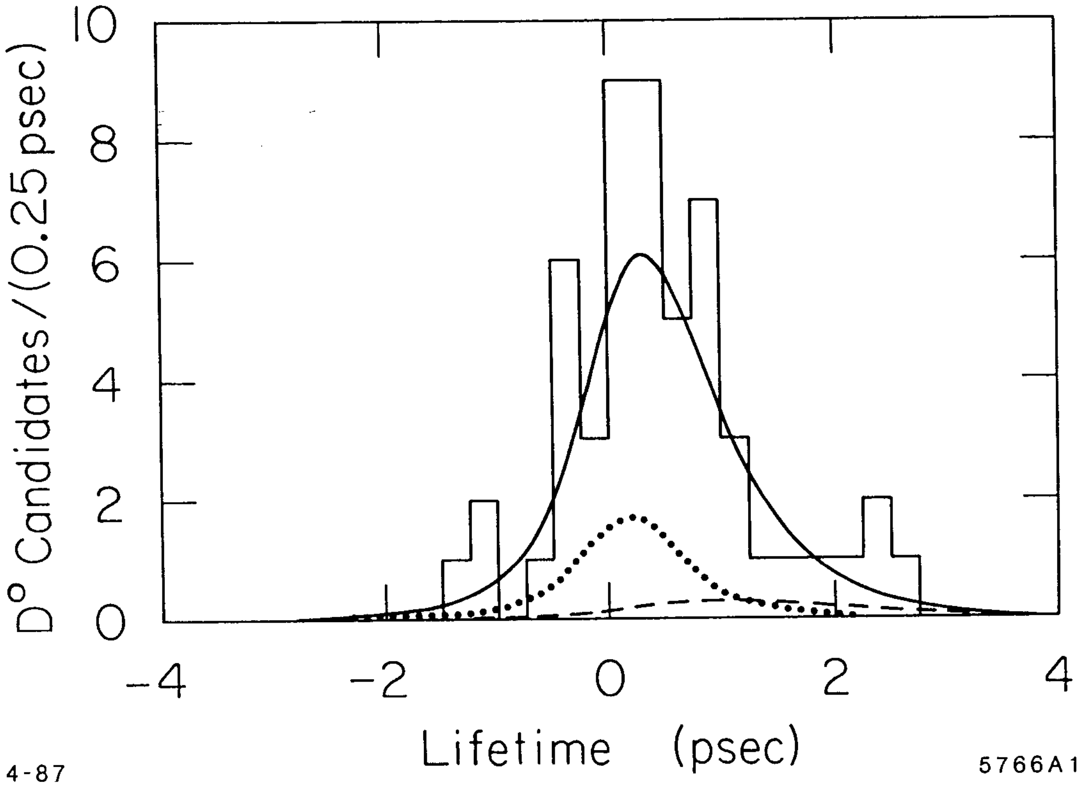

D° Candidates/(0.25 psec)
10
8
6
4
2
0
-4
-2
0
2
4
Lifetime (psec)
4-87
5766A1

Figure 2.