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Measurement of the D^0, D^+, and D_s^+ lifetimes

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We have measured the lifetimes of the D^0, D^+, and D_s^+ mesons which were produced by a high-energy photon beam incident on beryllium. Using the Fermilab Tagged Photon Spectrometer with a silicon-microstrip vertex detector we have collected 10^8 events from which we have extracted about 4200 D^0 decays in the $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ modes, 3000 D^+ into the $K^-\pi^+\pi^+$ channel, and a total of 230 D_s^+ into $\phi\pi^+$ and $\bar{K}^{*0}K^+$. From an analysis of these events we have determined the lifetimes for the D^0, D^+, and D_s^+ to be $0.422\pm0.008\pm0.010$, $1.090\pm0.030\pm0.025$, and $0.47\pm0.04\pm0.02$ psec, respectively.

I. INTRODUCTION

The singly charmed D^0, D^+, and D_s^+ mesons provide a unique opportunity to study the weak decays of the charm quark. Since the surprising discovery of different D^0 and D^+ lifetimes,[1] much theoretical and experimental work has been devoted to explaining and to obtaining better measurements of that difference. The lack of high-statistics data on charm lifetimes has impeded the development of realistic theories and their corresponding tests. Precise measurements of the D^0, D^+, and D_s^+ lifetimes provide important constraints on the various theoretical models of charm decay.

The obstacles to precise measurements of charmed-particle lifetimes have been a combination of low statistics, poor signal-to-noise ratios, and poor vertex resolution.[2] However, using the Tagged Photon Spectrometer (TPS) and silicon-microstrip detectors (SMD's) we have collected a large charm-rich data sample in experiment 691 (E-691) at Fermilab. We have extracted approximately 4200 D^0 decays in three modes, 3000 D^+ decays in a single channel, and 230 D_s^+ events in two modes. (Throughout this paper the charge-conjugate states are implicitly included.) In this paper we present our final results[3] from the lifetime analysis of these events.

In Sec. II of this paper we describe the apparatus and in Sec. III the event reconstruction. The common elements in the event selection for the different modes are given in Sec. IV. The method of extracting the lifetimes and the details particular to each mode are presented in Sec. V. A discussion of systematic errors follows. In Sec. VII we summarize our results and compare them to theoretical calculations.

II. EXPERIMENTAL APPARATUS

The TPS is a large-acceptance two-magnet spectrometer which was designed and built for a previous experiment, E-516 (Ref. 4). The upgraded version of the spectrometer as used by E-691 is shown in Fig. 1.

The photon beam was generated from the bremsstrahlung of 260-GeV/c electrons as they passed through a 0.2-radiation-length tungsten radiator. A set of magnets behind the radiator deflected the electrons into an array of shower counters where the final electron energy was measured. From this measurement and the electron beam energy, the radiated photon energy k was deduced. The photon energy spectrum extended from 90–260 GeV, and was roughly $1/k$ from 100 GeV on; the mean tagged photon energy was 145 GeV.

The most significant improvement to the TPS for the E-691 run was the installation of a vertex detector assembly.[5] We used nine silicon-microstrip detector planes with a 50-μm strip spacing. As shown in Fig. 2, the planes were arranged telescopically and alternately covered one of the three views, X (0°), Y (90°), and V (−20.5°). The angular acceptance of the system was about ±100 mrad. The signals from the strips were amplified, and discriminated at about half of the signal level produced by a minimum ionizing particle. We used modified multiwire-proportional-chamber (MWPC)

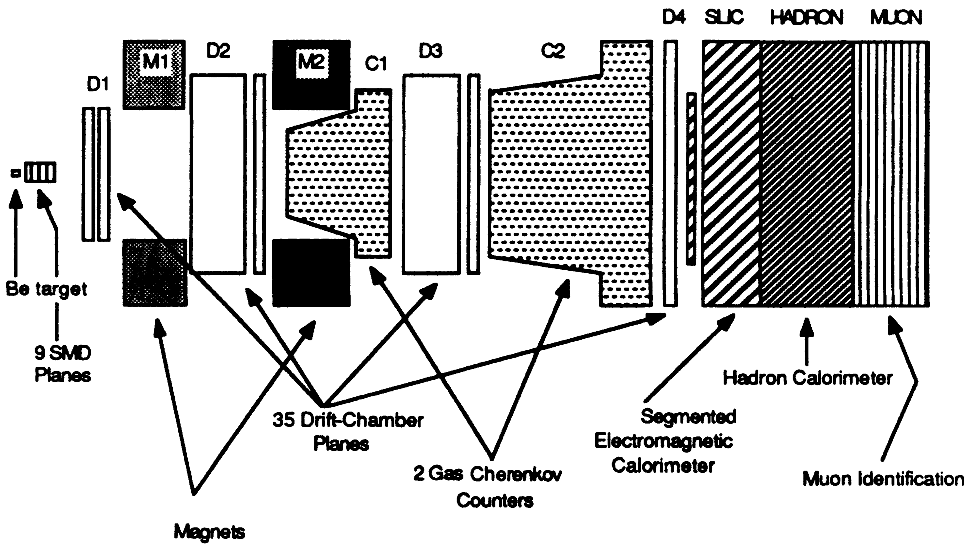

FIG. 1. Plan view of the Tagged Photon Spectrometer at Fermilab.

shift-register/discriminator cards to read out the strips: 3×512, 3×768, and 3×1000 channels from the upstream, middle, and downstream triplets, respectively. The downstream end of the 5-cm-long beryllium target was located 2.7 cm from the first microstrip plane, and the distance between the most upstream and downstream planes was 22 cm. Because of a ~95%-per-plane efficiency (dead channels accounted for over half of the 5% inefficiency) and a 14-μm intrinsic transverse resolution which was much smaller than typical transverse charm decay lengths of 150 μm, we were able to resolve the secondary vertex from the primary for typically half of the charm decays.

The TPS had four drift-chamber stations for downstream tracking and momentum measurements. The drift gas consisted of equal parts of argon and ethane, with a 1.5% admixture of ethanol for quenching secondary discharges. We had a total of 35 drift-chamber planes covering three views, X (0°), U(20.5°), and V (−20.5°): eight upstream of the first magnet, 12 in between the two magnets, 12 immediately downstream of the second magnet, and three in front of the calorimeters. The chamber-per-plane resolution and efficiency, as measured using reconstructed tracks, were about 300 μm and 90%, respectively. The upstream magnet had a horizontal and vertical acceptance of about ±240 and ±120 mrad, and the downstream magnet of about ±120 and ±60 mrad. The two magnets gave the charged particles horizontal momentum kicks of 0.21 and 0.32 GeV/c, respectively.

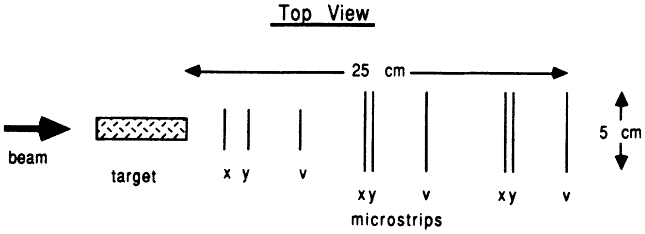

FIG. 2. Arrangement of the microstrip planes.

We used two threshold Cherenkov counters,[6] the upstream one with 28 cells and the downstream one with 32 cells. The upstream counter was filled with N_2 gas and had an index of refraction $n = 1.000\,309$. The second counter contained a mixture of 20% N_2−80% He by volume to give $n = 1.000\,090$. Narrow strips of baffling at beam height were stretched across the counters to absorb light from electrons created in beam photon conversions. The threshold momenta for the different particles are listed in Table I. We were able to separate pions from kaons and protons in the 6−37-GeV/c momentum region, and kaons from pions and protons between 20 and 37 GeV/c. The number of photoelectrons collected for highly relativistic particles was about 12 in each counter.

Two large calorimeters, a segmented lead–liquid-scintillator calorimeter[7] and an iron–acryllic-scintillator sandwich,[8] were used for electromagnetic- and hadronic-energy measurements. The electromagnetic (EM) calorimeter had a shower-position resolution of a few millimeters and an energy resolution of about $21\%/\sqrt{E}$ (E in GeV). We used it for π^0 and η reconstruction, and for electron identification. The hadron calorimeter had an energy resolution of about $75\%/\sqrt{E}$ (E in GeV) and was essential to the identification of muons and neutral hadrons. Both calorimeters were used in the main trigger of the experiment—a transverse-energy trigger. A linear array of shower counters placed at beam height in front of the EM calorimeter reduced the contamination of the trigger by e^+e^- pairs from beam photon conversions. Behind the hadron calorimeter a 1.0-m-thick iron wall

TABLE I. Threshold momenta for particles in the upstream and downstream Cherenkov counters.

	Threshold momenta (GeV/c) for				
Counter	e	μ	π	K	p
Upstream	0.02	4.2	5.6	20.0	37.7
Downstream	0.04	7.9	10.4	37.0	69.8

ranged out most hadrons, and was followed by a scintillator wall for muon detection.

The experiment was triggered if the total transverse energy deposited in the calorimetry was greater than about 2.2 GeV. The large-transverse-energy signal was required to be in coincidence with the following: a signal from a thin scintillation counter just downstream of the target to indicate the presence of at least one charged particle[9] (all signals were timed relative to the leading edge of this pulse); a light signal from the upstream Cherenkov counter to reduce false triggers from high-energy muons produced in a neighboring upstream experiment; and either a hadronic energy deposit greater than 40 GeV together with at least a 90-GeV beam photon, or—to circumvent the poor acceptance of the tagging system for very-high-energy photons—a hadronic energy deposit greater than 80 GeV. These requirements suppressed the false trigger rate from pair production by a factor of 200, leaving less than a 5% contamination in the final sample, and they rejected 70% of all hadronic interactions while retaining about 80% of the events with hadronic charm decays. (This was checked in detail for two-, three-, and four-body decays.) The difference in transverse energy between charm events and hadronic events is best illustrated in Fig. 3. The data for Fig. 3 were obtained from the reconstruction of hadronic events taken without the transverse-energy trigger.

During a three-month period we recorded about 10^8 events of which 10% were taken without the transverse-energy requirement. The data acquisitions were performed by a PDP-11/55 and monitored on a VAX 11/780. During a typical 22-sec spill we recorded about 2000 events on magnetic tape; usual event sizes were on the order of 1700 16-bit words. The data were reconstructed using the Fermilab Cyber system and the new microprocessor array developed by the Fermilab Advanced Computer Program.[10] The total reconstruction time per event on a single Cyber 175 was approximately 1.5 CPU seconds, and about 8 CPU seconds per microprocessor. Because 65–70% of all the data were reconstructed using this microprocessor system, the time delay to physics analysis with the full data set was reduced by a factor of 3.

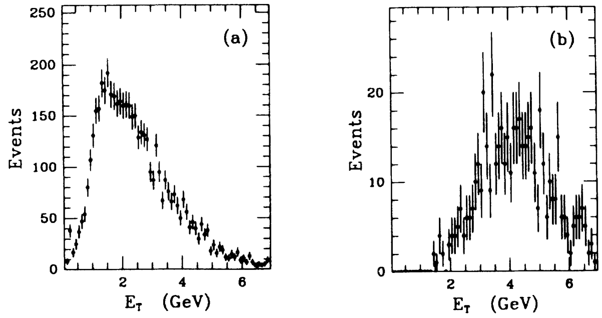

FIG. 3. Transverse energy of (a) all hadronic events, and (b) reconstructed charm events as obtained from data without the transverse energy trigger.

III. EVENT RECONSTRUCTION

Our track-finding procedure started in the SMD's. This method was chosen because of the low noise, high efficiency, and good resolution of the SMD's, and because the upstream field-free region had the largest number of planes: nine SMD and eight from the upstream drift chamber station in front of the first magnet.

The algorithm first searched for tracks with three hits in each SMD view. Given a set of three-hit tracks in two distinct views, the remaining view was examined at the predicted location for a three-, two-, or one-hit segment. On the next iteration three-two-one and two-two-two type combinations were explored. For the latter, the reconstruction had to rely on the first drift-chamber station for additional constraints, while needing less support for the nine-, eight-, and seven-hit segments with two three-hit views. The track segments were then projected through the spectrometer into the drift chambers using a single-bend-point approximation to the magnetic fields. Before the final momentum fit was performed a search was made for "drift-chamber-only" tracks from long-lived strange particles which decayed downstream of the SMD's.

For finding vertices, an accurate knowledge of the errors associated with the five track parameters (x and y intercepts, x and y slopes, and total momentum) was needed. From a detailed momentum fit we obtained

$$\frac{\Delta p}{p} \approx 0.050003p + 0.50003 \quad (p \text{ in GeV}/c) ,$$

and from a fit to only SMD hits we found, for typical errors at the downstream end of the target ($z \simeq 0$),

$$\sigma_x(z=0) \simeq 13 + \frac{50}{p\ (\text{GeV}/c)}\ \mu\text{m} ,$$

$$\sigma_{s_x}(z=0) \simeq 0.10 + \frac{3.3}{p\ (\text{GeV}/c)}\ \text{mrad} ,$$

$$\sigma_y(z=0) \simeq 16 + \frac{50}{p\ (\text{GeV}/c)}\ \mu\text{m} ,$$

$$\sigma_{s_y}(z=0) \simeq 0.13 + \frac{3.3}{p\ (\text{GeV}/c)}\ \text{mrad} .$$

For the slope and intercept, the second term in the errors accounted for multiple scattering in the target and was essentially negligible for tracks with momenta greater than 5 GeV/c. The last term in the momentum error stemmed from multiple scattering in the downstream spectrometer. For tracks which did not pass through the second magnet the momentum resolution was worse by a factor of 2, $\Delta p/p \approx 0.1\% p$ (p in GeV/c).

The vertexing algorithm took any two tracks with SMD hits and fit them to a common vertex using a least-squares method. As long as the χ^2 per degree of freedom of the fit remained below 3.0 other tracks were added—one by one—to the fit. If the additional track pulled the χ^2 over the threshold it was excluded from the current vertex but could still be included in another. A charm event as reconstructed in the SMD's is shown in Fig. 4. Typical errors on the vertices were approximately 15 μm transverse to the beam and 300 μm along the beam.

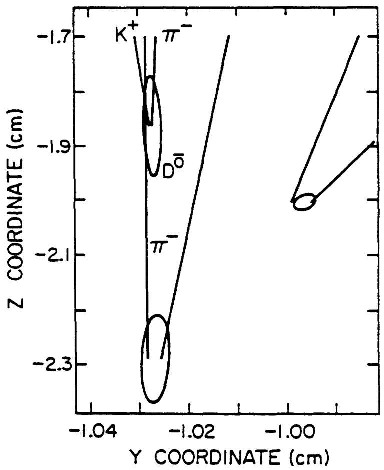

FIG. 4. A charm event as reconstructed in the SMD's. A $\overline{D^0} \to K^+\pi^-$, the additional π^- is from $D^{*-} \to \overline{D^0}\pi^-$; the ellipses represent the 1σ errors on the vertex position.

The charged hadrons were identified in the two Cherenkov counters. At the start of the Cherenkov reconstruction all tracks were assigned an *a priori* probability of 0.02, 0.01, 0.81, 0.12, or 0.04 to be an electron, muon, pion, kaon, or proton, respectively. These *a priori* probabilities corresponded to the average fractional occurrence of these particles in a typical hadronic interaction. A fit to the observed light distributions and light levels in the counters either raised or lowered these probability assignments, depending on whether the detected radiation was compatible or incompatible with a given mass hypothesis.

The reconstruction of showers in the electromagnetic calorimeter used a regression algorithm described in detail elsewhere.[11] Hadronic and electromagnetic particles were identified in the calorimetry by their characteristic shower shapes and penetration depths. The reconstruction efficiency for electrons with energy greater than 12 GeV was about 70%, and the detection and reconstruction efficiency for neutral pions with energy greater than 12 GeV was about 25% for clean low-multiplicity events, but only 10–11 % for charm events.

IV. EVENT SELECTION

In the first step of the selection we imposed general criteria on track quality, particle identification, and invariant mass. In the second step we applied vertex cuts which dramatically reduced the background, and we limited our fiducial volume to avoid regions of different efficiency.

We required that the number of degrees of freedom in the track fit be at least 12 out of a maximum of 39, or that the χ^2 of the fit be less than 8.0, or both. These cuts eliminated most spurious tracks for which a small number of hits had accidentally lined up. In order to make a vertex we demanded that the tracks were detected in the SMD's. Almost all tracks were required to pass through the upstream Cherenkov counter, so that some information on the particle identity was available; for two-particle mass combinations we required that the tracks pass through the second Cherenkov counter, while for three or more particle combinations we allowed for the escape of a single track into the region between the central two drift-chamber stations. For each decay mode, there was a minimum requirement on the product of the Cherenkov probabilities. The cuts on the joint probability were chosen to optimize the statistical significance of the signal. None of the lifetime results were sensitive to small changes in these cuts. The criterion always forced at least one particle to have a Cherenkov probability above the *a priori* assignment, and for the two-kaon D_s^+ modes constrained both kaons to be above their *a priori* probabilities. In Fig. 5 we show the joint probability distribution for $D^0 \to K^-\pi^+$ candidates. The cut, marked by the arrow, is well separated from the *a priori* peaks.

We demanded that the tracks of the charm candidate form a good vertex, with a χ^2 per degree of freedom less than 3.0. The remaining tracks in the event were combined into possible primary vertices. A search was made for all primary vertex candidates within a transverse distance of 75 μm from the line of flight of the reconstructed charm candidate. This selection on maximum transverse miss distance, or pointback, reduced the background by more than 60% while retaining about 80% of the charm decays. To further reduce the noncharm background, we kept only charm candidates that decayed at least a longitudinal distance $z_{\min}$ downstream of the primary vertex. The distance $z_{\min}$ was chosen to be $5-10\sigma_z$, depending on the decay mode, where σ_z is the longitudinal error on the distance L between the primary and the potential charm vertex as shown in Fig. 6. The value of σ_z was typically 300 μm for a D momentum of 60 GeV/c, corresponding to a proper-time resolution of about 0.03 psec. The longitudinal errors on the vertices increased almost linearly with momentum due to the time-dilation factor γ, but the significance of the vertex separations L/σ_z

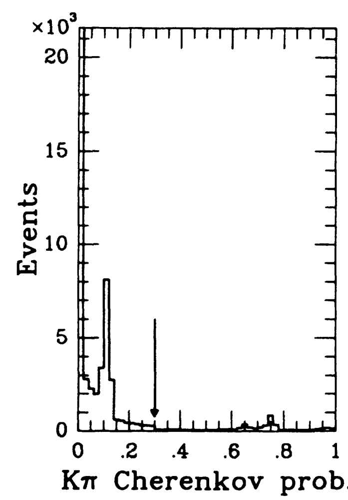

FIG. 5. Joint Cherenkov probability distribution for $D^0 \to K^-\pi^+$ candidates. The arrow marks the cut used in the event selection.

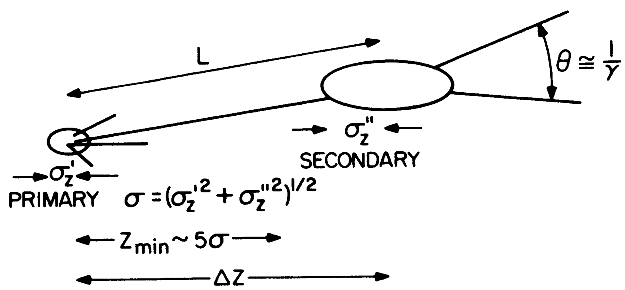

FIG. 6. Schematic of a production (primary) and a decay (secondary) vertex, and definitions of associated variables.

and the proper-time resolution were essentially constant.

In Fig. 7 we show a scatter plot of $\Delta z/\sigma_z$ versus mass for the $K\pi$ combinations, where Δz was the separation of the vertices in z. The enhancement at the D^0 mass is evident. The effect of increasing $z_{\min}$ on the signal and background is illustrated in Fig. 8. In the 20% of the events with multiple primary-vertex candidates, $z_{\min}$ was computed from the most downstream one to ensure that the chosen primary was not upstream of the true production point.

We calculated the proper time t from the point which was the distance $z_{\min}$ downstream of the primary vertex to the observed decay vertex

$$t=\frac{1}{\gamma v}(L-L_{\min}) ,$$

where $L_{\min}$ is the distance in the flight direction corresponding to $z_{\min}$. The shape of the time distribution was therefore insensitive to inaccuracies in the primary vertex position which were less than $z_{\min}$. (From our Monte Carlo simulation we found that mistakes larger than $z_{\min}$ occurred in about 1% of the events.) The fiducial region for decays was defined to end at the first SMD plane to avoid the region of partial detection and reconstruction efficiency beyond. In the D^0 and D_s^+ analysis we used only events for which the proper time corresponding to the end of this region, $t_{\max}$, was larger than the maximum time used in the fit 2.0 psec. For the D^+, the fit to the time spectrum extended to a maximum decay time of 4.0 psec, or about four lifetimes. As for the D^0 and D_s^+ we rejected events with $t_{\max}<2.0$ psec, but because of the longer D^+ lifetime and the extended time interval of the fit there was some loss of events at long lifetimes due to decays beyond the end of the fiducial region. This effect corresponded to a reduced, albeit calculable, efficiency between 2.0 and 4.0 psec, and was taken into account in the maximum-likelihood fit to the spectrum as described below.

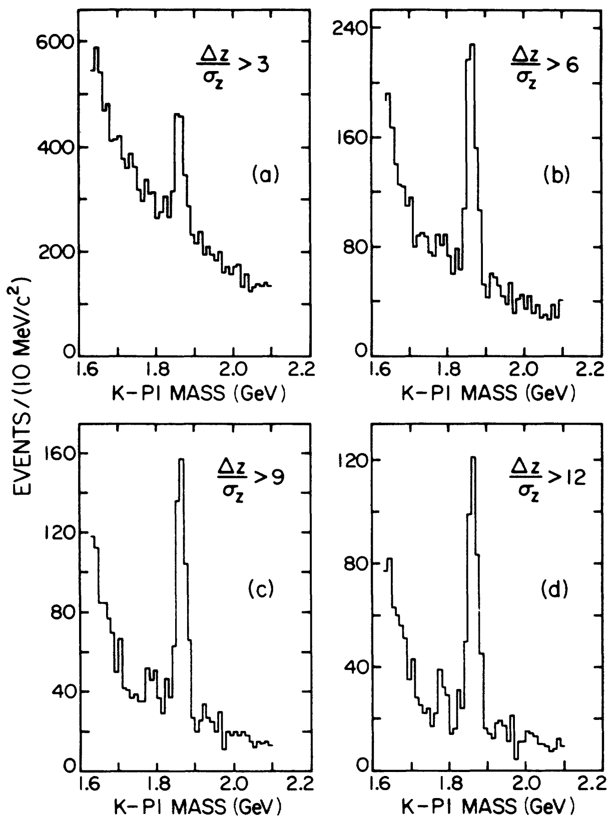

FIG. 8. The $K^+\pi^-$ invariant mass at four different values of $\Delta z/\sigma_z$.

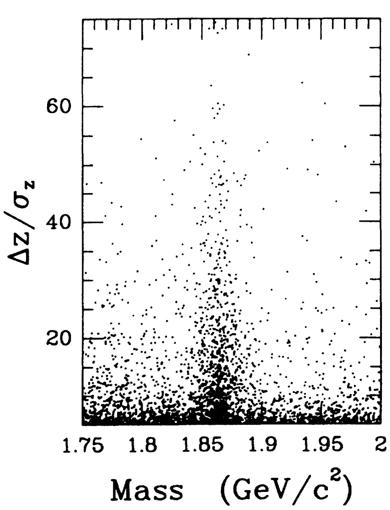

FIG. 7. Scatter plot of $\Delta z/\sigma_z$ vs $K^+\pi^-$ invariant mass. Note the higher density in the band centered at the D^0 mass.

Background events also have an effective value of t. These events are due to confusion with the tracks from the other charm particle, due to secondary interactions, or due to track-reconstruction errors and resolution.

V. LIFETIME ANALYSIS

We made a maximum-likelihood fit to the proper-time distributions of the form

$$N\frac{f(t)e^{-t/\tau}}{\int_0^{t_0}dt\, f(t)e^{-t/\tau}}+B(t) ,$$

where t_0 was the maximum time in the histogram, and where $B(t)$ was obtained from the time distribution of the background, as determined from events above and below the D-mass region in the mass plot, and was normalized to the signal region. The function $f(t)$, which was obtained from the Monte Carlo simulation, corrected for effects of absorption of the decay products, acceptance, resolution, and efficiency. We found that a linear function in t was a good parametrization for this correction:[12]

$$f(t)=\begin{cases}1.0+a(t-1.5), & t\leq 1.5 \text{ psec},\\ 1.0, & t>1.5 \text{ psec}.\end{cases}$$

This form was suggested by a calculation of the effects of absorption and acceptance of the decay products. Neglecting all other inefficiencies, absorption caused an exponential turn-on which became asymptotically flat near 1.5 psec. The slope a varied from mode to mode, and was determined from the Monte Carlo simulation. The free parameters in the fit were N, the number of events in the charm signal, and τ, the charm lifetime. The likelihood function was

$$\mathcal{L}=\prod_{i=1}^{k}\frac{(N_i)^{n_i}}{n_i!}e^{-N_i}$$

where N_i and n_i were, respectively, the predicted and observed number of events in bin i, corresponding to time t_i, and k was the number of bins, 20 in every case. For all modes we obtained good fits with a χ^2 per degree of freedom near 1.

A. D^0 analysis

For the D^0 lifetime study we used three modes:

$$D^{*+}\to\pi^+D^0,\quad D^0\to K^-\pi^+\ , \tag{1}$$

$$D^{*+}\to\pi^+D^0,\quad D^0\to K^-\pi^+\pi^-\pi^+\ , \tag{2}$$

$$D^0\to K^-\pi^+\quad (\text{no } D^{*+})\ . \tag{3}$$

Events which satisfied the requirements for set (1) were excluded from set (3), so the samples were statistically independent. For set (1) the mass difference $m(D^{*+})-m(D^0)$ was required to be between 0.144 and 0.147 GeV/c^2, and between 0.1435 and 0.1475 GeV/c^2 for set (2). The mass cuts were determined by optimizing the expected lifetime resolution using the Monte Carlo simulation to model the signal and the data to determine the background level. Table II presents the number of signal-and-background events in the mass range 1.842–1.886 GeV/c^2, the minimum decay length $z_{\min}$ used for each mode, and the lifetime results obtained from the maximum-likelihood fit. The mass distributions for the events which satisfied the vertex cuts are shown in Fig. 9. The slope a was 0.05, 0.20, and 0.08 (psec)$^{-1}$ for samples (1), (2), and (3), respectively.

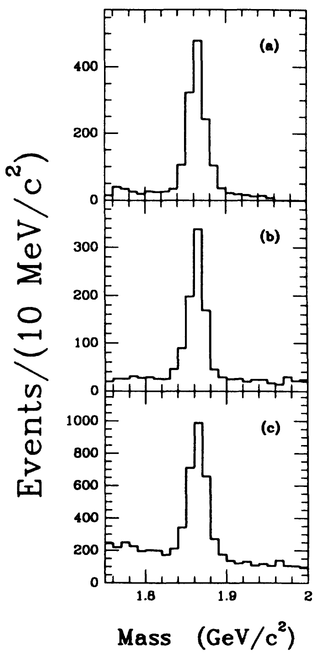

FIG. 9. Invariant-mass spectra for the three D^0 channels with vertex cuts as described in the text: (a) $D^{*+}\to\pi^+D^0$, $D^0\to K^-\pi^+$, (b) $D^{*+}\to\pi^+D^0$, $D^0\to K^-\pi^+\pi^-\pi^+$, and (c) $D^0\to K^-\pi^+$, no D^{*+}.

The proper-time distributions for the three D^0 channels after background subtraction are illustrated in Fig. 10. They have the expected exponential form. Considering that the channels had different corrections and backgrounds, the agreement of these three measurements within statistical errors provided confirmation as to the consistency of our method. A combined fit to all three samples gave the value, $\tau(D^0)=0.422\pm0.008$ psec, for the D^0 lifetime.

B. D^+ analysis

The decay mode

$$D^+\to K^-\pi^+\pi^+ \tag{4}$$

was used for the D^+ lifetime study. The mass spectrum for the accepted events, using a minimum decay length $z_{\min}=10\sigma_z$, is shown in Fig. 11. Because of the cut on the vertex separation $z_{\min}$, we obtained a background reduction factor of about 300. There were 2992±55 D^+ events in the selected mass region between 1.846 and

TABLE II. Characteristics of the D^0 samples; the errors are statistical.

Mode	$z_{\min}/\sigma_z$	No. signal	No. background	Lifetime (psec)
(1)	5	1210±36	94±5	0.417±0.014
(2)	7	700±27	113±5	0.437±0.019
(3)	8	2302±48	768±14	0.420±0.011

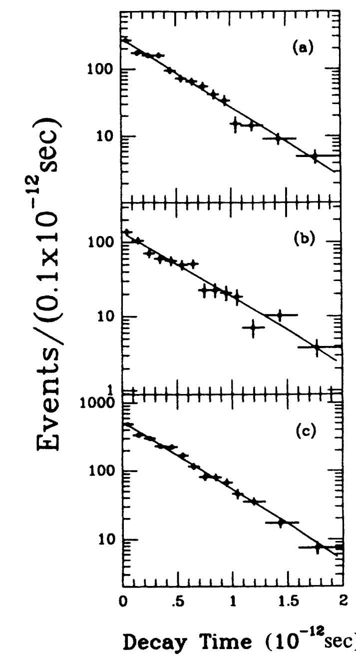

FIG. 10. Proper-time spectra for the three D^0 channels, in the same order as in Fig. 9. The data points are shown with background subtracted. The error bars represent the statistical error, including that on the background. The smooth curve represents the best fit as described in the text.

1.890 GeV. The number of background events, as determined from the number of events outside the D^+ region, was 1354±20.

The function $f(t)$ had two parts: the first, identical in form to that given above, accounted for losses at short times with slope $a = 0.17$ (psec)$^{-1}$; the second corrected for the loss of long-lived events. The latter was derived from the data and agreed with that obtained from the

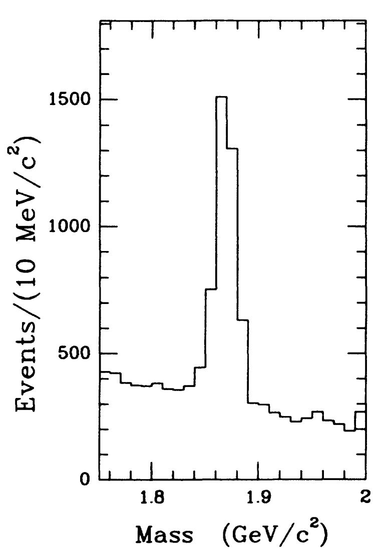

FIG. 11. Invariant-mass spectrum for $K^-\pi^+\pi^+$ for events used in the D^+ lifetime measurement.

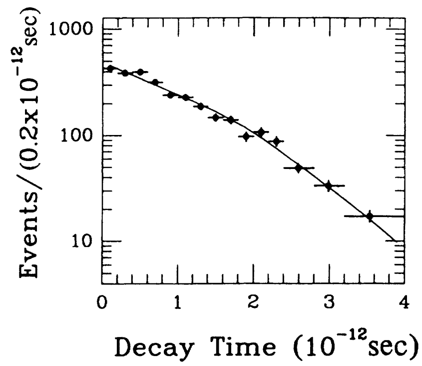

FIG. 12. Proper-time spectrum for D^+ events. The data points are shown with background subtracted as in Fig. 10. The smooth curve represents the best fit as described in the text.

Monte Carlo simulation. Because of the limited fiducial volume, the detection efficiency $\epsilon(t)$ was less than one for decays with $t \geq 2.0$ psec, and was given by the ratio of events which survived the fiducial cut at time t divided by the total. The resulting efficiency dropped linearly and was determined to be $\epsilon(t) = 1.0 - 0.22(t - 2.0)$ (t in psec), for $t \geq 2.0$ psec, and $\epsilon(t) = 1.0$ for $t < 2.0$ psec. The D^+ time distribution is shown in Fig. 12. The maximum likelihood fit gave a lifetime of 1.09±0.03 psec.

C. D_s^+ analysis

For the D_s^+ lifetime analysis, we used events consistent with one of the two decay modes

$$D_s^+ \to \phi\pi^+ , \quad (5)$$

$$D_s^+ \to \overline{K^{*0}} K^+ . \quad (6)$$

For channel (5) we required the K^-K^+ mass to be in the interval 1.012–1.027 GeV/c^2. The angular distribution for the decay $\phi \to K^-K^+$ is $dN/d(\cos\theta) = A\cos^2\theta$ where θ is the angle between the K^- and π^+ in the ϕ rest frame. We required $|\cos\theta| > 0.3$, which retained 97% of the signal and 70% of the background. For channel (6) we required the $K^-\pi^+$ mass to be in the interval 0.845–0.945 GeV/c^2. This range missed some of the K^* events but minimized the background. Again, we demanded that $|\cos\theta| > 0.3$, where θ is the decay angle between the K^- and K^+ in the K^* rest frame. There were no events in common mainly because of the vector-meson mass constraints, and because we did not use the few ambiguous events. In both samples we discarded events which were consistent with reflections due to K-π misidentification in the decays $D^{*+}(D^+) \to K^-\pi^+\pi^+$.

The mass distributions for both modes are shown in Fig. 13. In each plot there are clear peaks for the D_s^+ decay and for the Cabibbo-suppressed D^+ decay.[13] The time distributions for events in the mass region 1.953–1.985 GeV/c^2 are shown in Fig. 14. In Table III we list the minimum-longitudinal-vertex-separation significance, the number of signal and background events between 1.953 and 1.985 GeV/c^2, and the lifetimes as obtained from the fit. A joint fit to both distributions gave 0.47±0.04 psec for the lifetime. For these modes the

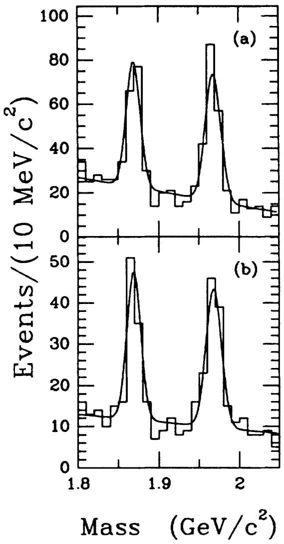

FIG. 13. Invariant-mass spectra for two D_s^+ channels with vertex cuts as described in the text: (a) $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$ and (b) $D_s^+ \to \overline{K}^{*0}K^+$, $\overline{K}^{*0} \to K^-\pi^+$.

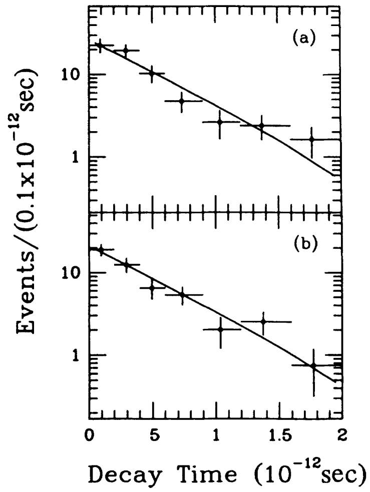

FIG. 14. Proper-time spectra for the two D_s^+ samples, arranged in the same order as in Fig. 13. The data points are shown with background subtracted. The error bars represent the statistical error, including that on the background. The smooth curve follows the best fit as described in the text.

function $f(t)$ had a slope $a = 0.27$ (psec)$^{-1}$ and $a = 0.23$ (psec)$^{-1}$, respectively.

VI. SYSTEMATIC ERRORS

We made a thorough analysis of our systematic errors using the data sample itself and the Monte Carlo (MC) simulation. The major sources of systematic errors were the background subtraction and the correction function $f(t)$. The shifts in lifetime due to the background subtraction and the correction function were in opposite directions and tended to cancel; in any case, the effect of $f(t)$ was always less than 15% of the lifetime.

A. Background subtraction

In the fit we floated the sum of the signal and background events. Thus, the statistical fluctuations in the background were included in the statistical error of the fit. However, there is an error associated with the average number of background events obtained from the finite number of events outside the signal region. All mass spectra were consistent with linear backgrounds. We did not increase the mass region to improve this error, because we could not guarantee that the nature of the background was constant over a wider mass range. Therefore, we had to include the errors on this average as systematic errors. For the D^* mode (1) the background subtraction had a negligible effect because of the small background and the very small lifetime difference between signal and background; it shifted the lifetime by $+0.013\pm0.001$ psec. For channels (2) and (3), it produced a shift of $+0.041\pm0.004$ and $+0.035\pm0.002$ psec, respectively. The errors were estimated by changing the number of background events by two standard deviations in either direction. Thus, the total effect of the background subtraction on the average D^0 lifetime was a shift of $+0.030\pm0.002$ psec. The background subtraction played a much larger role for the D^+ because the background had a considerably shorter effective lifetime than the signal. The total change amounted to $+0.275\pm0.017$ psec. For the D_s^+ the shifts for modes (5) and (6) were $+0.08\pm0.02$ and 0.03 ± 0.01 psec, respectively, and produced an integrated shift of $+0.060\pm0.015$ psec.

B. Correction function

The correction function accounted for the loss of events at short times due to absorption, acceptance, resolution, and vertex cuts. The size of the correction was obtained from the MC, and compared to direct estimates. The reconstructed MC samples had at least four times as many events as the data.

The MC-generated charm according to the photon-gluon-fusion model.[14] The Lund (Ref. 15) model was used to hadronize the quarks and gluons. The TPS was simulated in great detail—from multiple scattering in the

TABLE III. Characteristics of the D_s^+ samples; the errors are statistical.

Mode	$z_{\min}/\sigma_z$	No. signal	No. background	Lifetime (psec)
(5)	7.5	143±14	49±4	$0.45^{+0.05}_{-0.04}$
(6)	10	85±11	26±3	$0.49^{+0.08}_{-0.06}$

target and SMD's down to the last dead drift-chamber channel. The MC events were digitized, and then reconstructed with the same programs as those used for the data. In Fig. 15 we show a comparison between the data and the MC for the $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ mode. At this level there is good agreement. In Fig. 16 we have plotted the difference between the reconstructed proper time and the generated MC time. The width of this distribution is a direct measure of the proper-time resolution. We tested our sensitivity to the production model by fitting the lifetimes in different momentum regions. The results are presented in part (a) in Table IV. Part (b) in Table IV gives the measured lifetimes for different bins in the number of reconstructed vertices. Changes in the charged-particle multiplicity had no effect on the observed lifetimes. We do not observe any significant systematic trends outside the statistical errors.

In Table V we list the contributions to the slope a from various sources. The last two columns contain the total a, as obtained from the MC, and the corresponding shifts in lifetime. The effect of absorption of decay particles in the target, denoted by a_{abs}, was computed from known cross sections,[16] and typically accounted for one-half to one-third of the total correction. The detection of long-lived, as compared with short-lived, decays was enhanced by absorption because the decay products had less material to traverse, and thus were less likely to interact. We neglected the absorption of the charmed particles because of the smaller cross sections. We also estimated the effect of the differing geometric acceptance between the upstream and downstream ends of the target by moving the decay upstream until, either, one of the wide-angle decay products did not pass through the SMD's, or, the end of the target was reached. This effect also biased against upstream decays and short-lived ones. The acceptance contribution to the correction, a_{acc}, was fairly small, and increased slightly with the particle multiplicity of the decay.

In Table V we include the effect of the z_{min} vertex cuts on the corrected lifetimes; this was a higher-order effect because of the small momentum dependence of the vertex errors from multiple scattering. We were completely insensitive to the cuts on the χ^2 of the charm vertex and on the pointback. The estimated contribution to the correction a_z due to the z_{min} cut is listed in column four of Table V. We also investigated the shifts in lifetime due to selecting the wrong primary vertex. From the MC we found that in D^* events less than 1.5% of the events had the real primary vertex outside z_{min}; in the other modes this occurred for less than 0.5% of the events. The column, titled a_{fvtx}, in Table V gives an estimate of the size of this effect. Upon adding columns two through five and the errors in quadrature to obtain column six in Table V we note that this semiquantitative approach is in

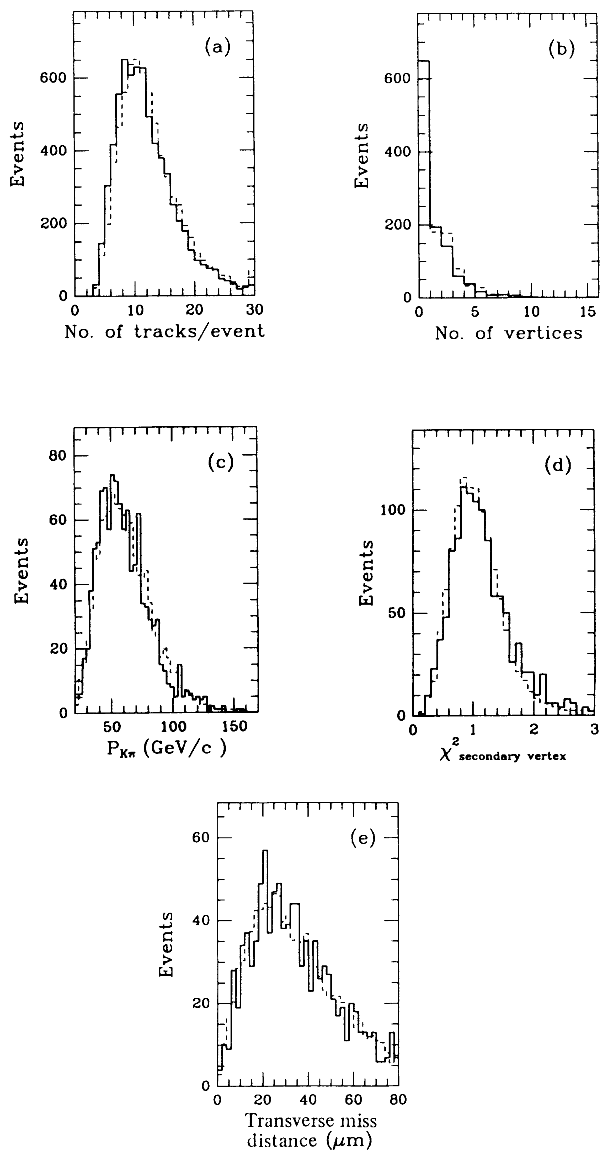

FIG. 15. Comparison of Monte Carlo simulation (dashed) and background-subtracted data (smooth) for the $D^{*+} \to \pi^+ D^0$, $D^0 \to K^- \pi^+$ modes: (a) number of tracks per event, (b) number of vertices per event, (c) total momentum, (d) χ^2 of the secondary vertex, and (e) transverse miss distance.

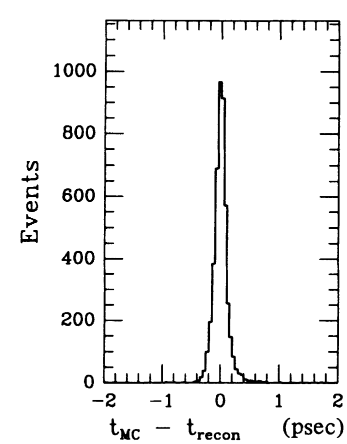

FIG. 16. Difference between the generated Monte Carlo proper time and the reconstructed proper time.

TABLE IV. (a) The lifetimes (psec) for different momentum intervals. (b) The lifetimes (psec) for different vertex multiplicity intervals.

	(a) Momentum regions		
Particle	20–58 GeV/c	58–68 GeV/c	68–140 GeV/c
D^0	0.42±0.02	0.41±0.03	0.42±0.02
D^+	1.06±0.06	1.09±0.05	1.06±0.04
D_s^+	0.53±0.10	0.38±0.07	0.46±0.08
	(b) Number of reconstructed vertices		
Particle	2	3–4	5–18
D^0	0.42±0.02	0.42±0.03	0.44±0.03
D^+	1.04±0.03	1.17±0.07	1.06±0.09
D_s^+	0.52±0.09	0.45±0.07	0.43±0.12

fair agreement with the corrections obtained directly from the MC. The MC results were the most reliable measurement of the correction for all effects, and were used in the lifetime fits.

As a consistency check the correction for the inefficiency at long decay times of the D^+ was crudely estimated from geometric considerations alone. From the agreement between the data, the MC, and the naive calculation we estimated our error on the slope of the efficiency function at 10%, corresponding to a negligible error on the D^+ lifetime of ±0.003 psec.

The input lifetimes to the MC were 0.44, 1.10, and 0.40 psec for the D^0, D^+, and D_s^+, respectively. From studies on the D_s^+ and the D^+ we found that the final lifetime results were not very sensitive to changes in the input MC lifetime. A 20% change of the MC D_s^+ lifetime from 0.40 psec to 0.48 psec did not change the final D_s^+ result, and a 15% shift in the D^+ MC lifetime changed the corrected D^+ lifetime well within statistical errors.

C. Misidentification

Because we had almost full particle-identification capabilities in the appropriate momentum region, and because we used only well-identified particles, we did not have the visible reflections which are common in e^+e^- experiments. In fixed-target experiments the reflections are also much broader due to the larger range in laboratory momenta of the particles. The $KK\pi$ decay modes of the D_s^+ are most sensitive to π-K misidentification which causes the reflection of the $D^+ \to K^-\pi^+\pi^+$ decays to produce a longer effective D_s^+ lifetime, and to p-K confusion which reflects the Λ_c^+ down and shifts the observed lifetime down. These reflections had a width of a few hundred MeV/c^2, much wider than the widths of the mass peaks. On account of these difficulties we used only the resonant modes (5) and (6) rather than including the nonresonant events for the D_s^+ lifetime measurement. Extensive studies using both data and MC showed that about two events and one event, in both modes combined, could be attributed to the above sources, respectively. In addition, the background subtraction reduced this effect further, so that the resulting contributions to the total systematic error were negligible.

Combining all the above errors in quadrature, we estimate our total systematic errors on the lifetime measurements of the D^0, D^+, and D_s^+ at 0.010, 0.025, and 0.02 psec, respectively.

TABLE V. Contributions to the parameter a (psec^{-1}) in the correction function $f(t)$: direct estimates and the Monte Carlo results. The quantity $\Delta\tau_{MC}$ is the shift in lifetime in psec.

Mode	a_{abs}	a_{acc}	a_z	a_{fvtx}	a_{tot}	a_{MC}	$\Delta\tau_{MC}$
(1)	0.04	0.015	0.01	0.02	0.08	0.05	0.010
	±0.01	±0.010	±0.02	±0.01	±0.03	±0.02	±0.004
(2)	0.10	0.04	0.05	0.03	0.22	0.20	0.050
	±0.015	±0.02	±0.030	±0.02	±0.04	±0.03	±0.008
(3)	0.04	0.015	0.05	0.01	0.11	0.08	0.014
	±0.01	±0.010	±0.02	±0.01	±0.03	±0.02	±0.004
(4)	0.07	0.02	0.04	0.00	0.13	0.17	0.14
	±0.01	±0.01	±0.02	±0.01	±0.03	±0.02	±0.02
(5)	0.08	0.03	0.04	0.02	0.17	0.27	0.080
	±0.01	±0.02	±0.05	±0.01	±0.06	±0.05	±0.017
(6)	0.08	0.03	0.04	0.02	0.17	0.23	0.080
	±0.01	±0.02	±0.05	±0.01	±0.06	±0.05	±0.017

TABLE VI. Summary of the D lifetimes.

Particle	Lifetime (psec)	Statistical error (psec)	Systematic error (psec)
D^0	0.422	±0.008	±0.010
D^+	1.090	±0.030	±0.025
D_s^+	0.47	±0.04	±0.02

VII. SUMMARY AND CONCLUSIONS

Our lifetimes for the D^0, D^+, and D_s^+ are summarized in Table VI. The D^0 and D^+ measurements are consistent with our previous results,[3] and the world averages[17] of $0.43^{+0.05}_{-0.04}$ and $0.94^{+0.11}_{-0.08}$ psec, respectively. The D_s^+ lifetime is almost twice the world average of $0.28^{+0.16}_{-0.07}$ psec, although it is in better agreement with more recent measurements.[18] We observe that the D^0 and the D_s^+ lifetimes are equal within errors, which may indicate a fundamental similarity in the decay processes.

For comparison with theoretical models and partial decay widths, we have computed our lifetime ratios $\tau(D_s^+)/\tau(D^0)=1.11\pm0.10\pm0.04$ and $\tau(D^+)/\tau(D^0)=2.58\pm0.09\pm0.08$. This latter ratio has been inferred from semileptonic branching ratios[1]; ignoring the Cabibbo-suppressed annihilation process with final-state leptons for the D^+,

$$\tau(D^+)/\tau(D^0)=B(D^+\to e^+X)/B(D^0\to e^+X)$$
$$=2.3^{+0.5}_{-0.4}\pm0.1\ ,$$

as measured by Mark III (Ref. 19).

The spectator-quark model[20] correctly predicts the order of magnitude of charm-particle lifetimes, but in its simplicity fails to account for the different observed lifetimes. To explain these differences various attempts have been made to improve the model either by suppressing the D^+ decays, or enhancing the D^0 modes, or both.

The suppression of the D^+ decays is achieved via destructive interference of two amplitudes with identical final states.[21] The enhancement of the D^0 is accomplished by increasing the contribution of the W-exchange process. This process is usually ignored because of the helicity suppression at the light-quark vertex and because of the required large overlap of the quark wave functions in the original hadron. However, some models claim that gluon radiation removes those constraints.[22] In another approach[23] it has been proposed that there is a sizable general nonleptonic enhancement of all charm decays from QCD corrections which is almost exactly canceled by the interference effect for the D^+. It is uncertain what influence final-state interactions have on the lifetimes;[24] that they play an important role for individual decay modes seems to be substantiated by the large $D^0\to\phi\bar{K}^0$ branching ratio.[25]

The various models make different predictions for the D_s^+ semileptonic branching ratios and lifetime. If W exchange/annihilation is dominant, then a large semileptonic branching ratio for $D_s^+\to Xe^+\nu$ is expected, and the D_s^+ lifetime should be less than or equal to that of the D^0 (Ref. 26). The interference effect alone, while partially explaining the D^0-D^+ lifetime discrepancy, cannot reproduce the small semileptonic branching ratio of the D^0 as observed by Mark III (Ref. 19). However, interference together with nonleptonic enhancement from QCD corrections could account for the observed semileptonic branching ratios and lifetimes.

Lifetime measurements alone are insufficient to distinguish clearly among the different models. For example, the W annihilation/exchange mechanism predicts lifetime ratios, but contains two free parameters which determine the strength of the color-singlet and -octet couplings to the emitted gluon. Now that detailed predictions of branching ratios are available,[23,27,28] it is expected that precise measurements of semi and nonleptonic modes, especially those of the D_s^+, together with the lifetimes, will lead to a concise picture of charm decay.

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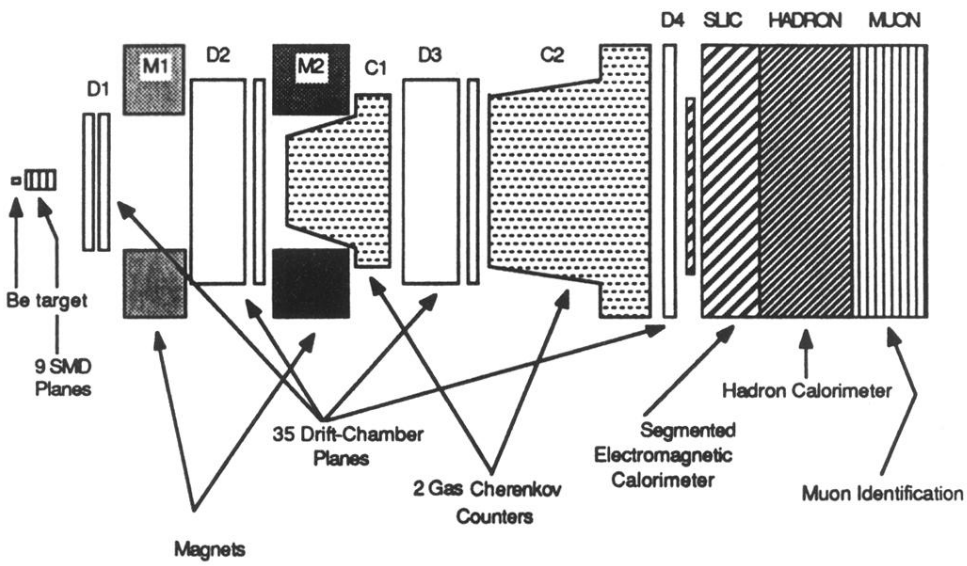

FIG. 1. Plan view of the Tagged Photon Spectrometer at Fermilab.