Evidence for Unequal Lifetimes of the D^0 and D^+

W. Bacino, T. Ferguson,[a] L. Nodulman,[b] W. Slater, and H. Ticho
Physics Department, University of California, Los Angeles, California 90024

and

A. Diamant-Berger,[c] G. Donaldson, M. Duro, A. Hall,[d] G. Irwin,
J. Kirkby, F. Merritt,[e] and S. Wojcicki
Stanford Linear Accelerator Center and Physics Department, Stanford University, Stanford, California 94305

and

R. Burns,[f] P. Condon,[g] and P. Cowell[h]
Physics Department, University of California, Irvine, California 92664

and

J. Kirz
Physics Department, State University of New York, Stony Brook, New York 11794

(Received 28 April 1980)

In the reaction $e^+e^- \rightarrow \psi''(3770)$, events containing either one to two electrons have been observed originating in semileptonic decays of D mesons. A comparison of these samples provides a determination of the branching ratios: $b(D^0 \rightarrow Xe\nu) < 4.0\%$ (at 95% confidence level) and $b(D^+ \rightarrow Xe\nu) = (22.0^{+4.4}_{-2.2})\%$. These values imply that the ratio of D^0 and D^+ lifetimes is $\tau(D^+)/\tau(D^0) > 4.3$ (at 95% confidence level).

PACS numbers: 14.40.Pe, 13.65.+i

The conventional model of the decay of charmed mesons[1] assumes that the light quarks are merely spectators and therefore predicts the D^0 and D^+ lifetimes to be equal. We report here a measurement of unequal lifetimes from a study of $D\bar{D}$ pairs produced in e^+e^- annihilations.[2] The analysis is based on a comparison of two data samples: In one, both D and $\bar{D}$ decay semileptonically, leading to events with a detected e^+ and e^- ("2*e* events"); in the other, only one semileptonic decay is observed ("1*e*"). The data, recorded by the DELCO detector[3] at SPEAR, are selected from energies at the ψ'' and below. The ψ'' provides a pure sample of $D\bar{D}$ events with known charged and neutral composition, and the lower-energy data are used in the background measurements.

The selection criteria for the 1*e* sample[4] require that events contain ≥ 3 observed charged tracks, of which one is identified as an electron by having in-time Cherenkov- and shower-counter pulses. The backgrounds to the 1*e* sample come largely from τ decays, accidental coincidences of a hadronic track and a Cherenkov pulse, misidentified photon conversions and Dalitz decays, and two-photon processes. Subtracting contributions from these backgrounds, we obtain 734 ± 44 1*e* events due to charm decays at the ψ''.

Events in the 2*e* sample must have two electrons and at least one nonelectron, defined as a track having momentum above 200 MeV/*c*, which passes through the Cherenkov counter but produces no Cherenkov pulse. To obtain unambiguous electron identification, we demand that only one track enter each triggered Cherenkov cell. The candidates are scanned to eliminate the majority of $ee\gamma$ final states and misidentified photon conversions in hadronic events. A background due to $\psi' \rightarrow \psi\pi^+\pi^- \rightarrow e^+e^-\pi^+\pi^-$ is reduced by requiring an acollinearity of at least 20° between the e^+ and e^- in the azimuthal projection. Events involving π^0 or η Dalitz decays are suppressed by requiring that the electron pair mass exceed m_{π_0}. 21 2*e* events satisfy these criteria at the ψ''.

The residual backgrounds in the 2*e* events result from (1) two real electrons, such as from two-photon processes or Dalitz decays; (2) one real electron plus one false electron, such as a D or τ decay together with a hadron misidentified as an electron; and (3) two false electrons. We study 1*e* events at the $\psi(3100)$ to determine the misidentification probability for a track as an electron (1.9×10^{-3}). Backgrounds (2) and (3) are then measured from the 1*e* sample at the ψ'' by randomly assigning a Cherenkov tag to eligible tracks at a rate equal to this misidentification probability. The resulting events are subjected to requirements identical to the actual 2*e* data sample. This technique has the advantage of including the proper mixture of electrons from D and τ decays and from backgrounds such as photon conversions. The contribution from two-photon events is determined by a Monte Carlo calculation.[5] Finally any remaining backgrounds are determined from the residual $2e$ events observed at the ψ and ψ' after subtracting all the other backgrounds. The results of these calculations, which are summarized in Table I, indicate that 16.4 ± 4.6 $2e$ events at the ψ'' are due to both D and $\bar{D}$ decaying semileptonically.

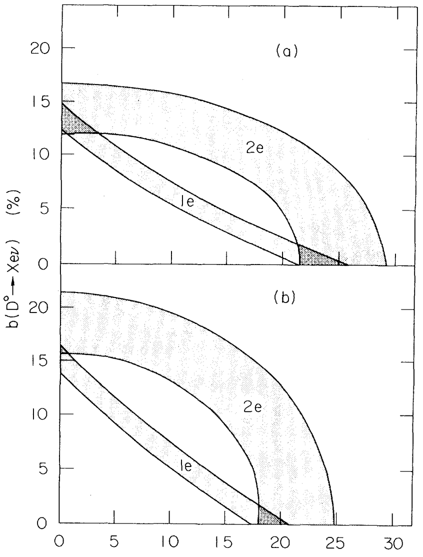

FIG. 1. The values (shaded area) of b^0 and b^+ which correspond to ± 1-standard-deviation (1σ) statistical variations in the observed number of $1e$ and $2e$ events. The data are shown under two extreme assumptions for the detection efficiencies: (a) all semileptonic D decays occur as $D\to Ke\nu$; (b) all semileptonic D decays occur as $D\to K^*e\nu$.

The values of the D^0 and D^+ semileptonic branching ratios (b^0 and b^+, respectively) are determined by finding a common solution to the following expressions for the number of $1e$ events (N_{1e}) and $2e$ events (N_{2e}) after background subtractions:

$$N_{1e} = N_0\epsilon_1{}^0 2b^0(1-b^0) + N_+\epsilon_1{}^+ 2b^+(1-b^+) + \text{smaller terms in } b^2, \quad (1)$$

$$N_{2e} = N_0\epsilon_2{}^0 b^{0\,2} + N_+\epsilon_2{}^+ b^{+\,2}, \quad (2)$$

where N_0 and N_+ are the number of produced $D^0\bar{D}^0$ and D^+D^- pairs[6] from which the data sample is drawn. The efficiency $\epsilon_1{}^0$ ($\epsilon_1{}^+$) is the probability of detecting a $1e$ event from a $D^0\bar{D}^0$ (D^+D^-) initial state in which only one D decays to an electron. ($\epsilon_2{}^{0,+}$ is defined similarly for $2e$ events.) The smaller terms in Eq. (1) are due to the correction for events involving two semileptonic decays but with only one detected electron. The allowed regions for b^0 and b^+, as deduced from Eqs. (1) and (2), are shown as shaded bands[7] in Fig. 1. The bands correspond to $\pm 1\sigma$ statistical variations in the number of observed events. The data are displayed for two extreme assumptions which affect the detection efficiencies: Either all events originate as $D\to Ke\nu$ or all as $D\to K^*e\nu$. The data show that either $b^0 \gg b^+$ or $b^+ \gg b^0$, and the regions of overlap are approximately independent of the K vs K^* assumption. In order to assess the statistical significance of this result, we calculate the probability of observing 21 or more $2e$ events (including background) if $b^0=b^+$. For $b^0=b^+=8\%$,[2] the predicted number of $2e$ events is 10.7 for which the corresponding probability is 0.3%. If we take $b^0=b^+=9.1\%$ (1σ above the world average value), the predicted number is 12.3 which gives a probability of 1.5%. It is therefore unlikely that the excess $2e$ events are a statistical fluctuation.

The ambiguity of which branching fraction is the larger one is resolved by measuring the K^0 yield, which in general is different for D^+ and D^0 semileptonic decays. We identify a $K_s{}^0$ decay by the presence of a V, defined as one or two "detached" tracks, which do not point back to the origin in the azimuthal view. A Monte Carlo simulation indicates that typically only one detached track is

TABLE I. Summary of the $2e$ data sample.

	$2e$ events		$2e$ events with $K_s{}^0$	
$E_{\text{c.m.}}$	Observed	Calculated backgrounds	Observed	Calculated backgrounds
$\psi+\psi'$	14	14 ± 3.1	4	3.8 ± 0.7
3.50 → 3.67 GeV	2	1.9 ± 1.1	0	0.0 ± 0.1
ψ''	21	4.6 ± 0.9	8	2.1 ± 0.7

observed from the decay $K_s^0 \to \pi^+\pi^-$, since the other prong frequently either misses the detector or aligns with the event vertex. Of the 21 $2e$ events, 8 have a V.

The backgrounds of the $2e + V$ events consist of (a) false V's with real or false electrons, or (b) real V's with at least one false electron. False V's result mainly from particle interactions in the beam pipe, or from in-time cosmic rays which traverse only part of the cylindrical chambers. These contributions to the false V probability are determined from the fraction of $\psi' \to \pi^+\pi^- \to e^+e^-\pi^+\pi^-$ events which exhibit a detached track. Background (a) (1.2 events) is then determined from the product of the number of $2e$ events and this false V probability, with an additional small correction for charm-produced $K^\pm$ decays (0.3 events). Background (b) (0.6 events) is the product of the number of $2e$ background events and the probability of a real V, which is determined by a measurement of the $1e + V$ rate at the ψ''. After subtracting the backgrounds, we find that 5.9 ± 2.1 events contain two electrons and a detected K_s^0 decay. The expected numbers, under different decay-mode assumptions, are shown in Table II. We see that this large K_s^0 signal implies both that the solution $b^+ \gg b^0$ is favored and that $D^+ \to \bar{K}^0 e^+ \nu$ is an important decay mode.

To determine the branching ratios, we form a statistical likelihood function $L(b^0, b^+)$ which is the product of the probabilities to observe three quantities: (a) N_{1e} (with a Gaussian probability density), (b) N_{2e} (Poisson) and, (c) the number of $2e + V$ events given an observed signal of 16.4 $2e$ events (Poisson). This computation depends on the ratio $r_K = \Gamma(D \to Ke\nu)/\Gamma(D \to Xe\nu)$, and we take $r_K = (0.6 \pm 0.2)$.[4,8] Systematic errors in this parameter and in other numbers such as normalization, Cherenkov efficiency, and $D^0\bar{D}^0$: D^+D^- ratio are treated by including additional factors in the likelihood function. All these parameters are then varied along with b^0 and b^+ in the likelihood analysis. The result is displayed in Fig. 2, which shows the projection of equal-probability contours in b^0 and b^+ corresponding to χ^2 variations of 1 and 4, where $\chi^2 = -2\ln L(b^0, b^+)$. The D^0 and D^+ semileptonic branching ratios are found to be $b^0 < 4.0\%$ [at 95% confidnece level (C.L.)] and $b^+ = (22.0^{+4.4}_{-2.2})\%$, respectively. The lower limit for the ratio b^+/b^0 is 4.3 (95% C.L.).

TABLE II. Predicted number of $2e + V$ events for different decay modes. The probability of observing 8 or more $2e + V$ events given the predicted number. The calculation is based on 16.4 charmed $2e$ events and includes a background of 1.8 – 2.6 depending on the initial state and decay mode.

Initial state, decay mode	Predicted $2e + V$ events (including background)	Probability (%)
D^+D^-, $D \to Ke\nu$	7.9	53
D^+D^-, $D \to K^*e\nu$	3.7	3.5
$D^0\bar{D}^0$, $D \to Ke\nu$	2.6	0.5
$D^0\bar{D}^0$, $D \to K^*e\nu$	3.8	4.0

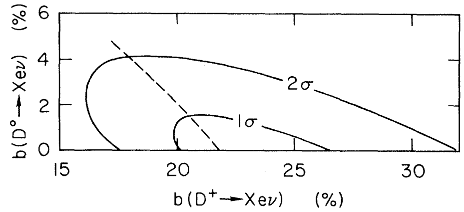

FIG. 2. Probability contours corresponding to χ^2 changes of 1 and 4 (1σ and 2σ in b^0 and b^+) calculated from the likelihood function for observing the measured number of $1e$, $2e$, and $2e + V$ events. Both the statistical and systematic uncertainties have been included. The dashed line indicates the best value for b^+ vs b^0.

Isospin symmetry leads to equal D^0 and D^+ semileptonic rates, and so these measurements imply that the D^+ lifetime is greater than the D^0 lifetime: $\tau(D^+)/\tau(D^0) > 4.3$ (95% C.L.), presumably due to a stronger hadronic enhancement in D^0 decay. The actual lifetimes may be derived from the theoretical rate,[9] $\Gamma(D \to Ke\nu) = 1.4\ 10^{-11}\ \mathrm{sec}^{-1}$, which yields $\tau(D^0) < 2.1 \times 10^{-13}$ sec (95% C.L.), and $\tau(D^+) = (10.4^{+3.9}_{-2.9}) \times 10^{-13}$ sec. These results are in agreement with the direct lifetime measurements made in the Fermilab ν-emulsion experiment[10] and with the semileptonic branching ratios obtained by the SPEAR Mark II collaboration.[8]

We gratefully acknowledge the services of the Stanford Linear Accelerator Center Experimental Facilities Division, the SPEAR Operations Group, and Stanford Linear Accelerator Computing Center. This work was supported in part by the National Science Foundation, and by the U. S. Department of Energy under Contract No. DE-AC03-76SF00515.

---

[a] Current address: Cornell University, Ithaca, N.Y. 14853.

[b] Current address: Argonne National Laboratory,

Argonne, Ill. 60439.

(c)Permanent address: Centre d'Etudes Nucléaires de Saclay, Saclay, France.

(d)Current address: Varian Associates, Palo Alto, Cal. 94303.

(e)Current address: University of Chicago, Chicago, Ill. 60637.

(f)Current address: Hughes Aircraft Co., Newport Beach, Cal. 92663.

(g)Current address: Lawrence Berkeley Laboratory, Berkeley, Cal. 94720.

(h)Current address: Systems Control, Inc., Palo Alto, Cal. 94303.

[1] N. Cabibbo and L. Maiani, Phys. Lett. 73B, 418 (1979).

[2] Preliminary results were presented by J. Kirby, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill., 1979).

[3] W. Bacino *et al.*, Phys. Rev. Lett. 40, 671 (1978).

[4] W. Bacino *et al.*, Phys. Rev. Lett. 43, 1073 (1979).

[5] We thank J. A. M. Vermaseren for calculations of the two-photon cross sections.

[6] We take the $D^0\bar{D}^0$:D^+D^- ratio to be (0.56± 0.03):(0.44 ± 0.03), according to phase space. The total data sample consists of 15.4×10^3 produced $D\bar{D}$ pairs. This is derived from the hadronic cross section at the ψ'' in conjunction with Monte Carlo calculations of hadronic efficiencies. The phase-space model used in the efficiency calculation has been adjusted to reproduce the multiplicity distributions reported by the Mark I collaboration. See J. Siegrist, Ph.D. thesis, Stanford University, SLAC Report No. 225, 1979 (unpublished); V. Lüth, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill. 1979).

[7] The asymmetry of the linear and elliptical regions arises partly due to the difference in the neutral versus charged production rates, and partly due to different experimental detection efficiencies for the D^0 and D^+ modes.

[8] See R. Schindler, Ph.D. thesis, Stanford University, SLAC Report No. 219, 1979 (unpublished); Lüth, Ref. 6.

[9] D. Fakirov and B. Stech, Nucl. Phys. B133, 315 (1978).

[10] J. Prentice, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Batavia, Illinois, 1979,* edited by T. B. W. Kirk and H. D. I. Abarbanel (Fermilab, Batavia, Ill., 1979).

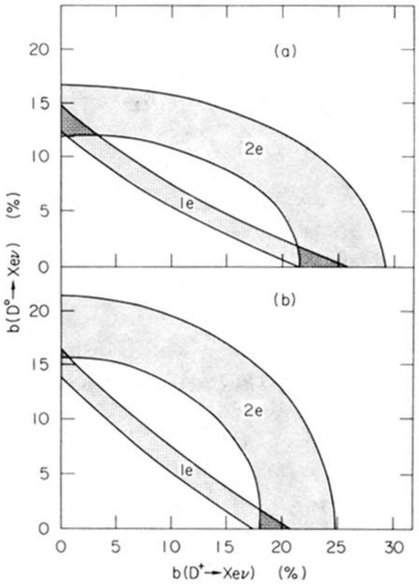

FIG. 1. The values (shaded area) of b^0 and b^+ which correspond to ± 1-standard-deviation (1σ) statistical variations in the observed number of 1*e* and 2*e* events. The data are shown under two extreme assumptions for the detection efficiencies: (a) all semileptonic *D* decays occur as $D \to Ke\nu$; (b) all semileptonic *D* decays occur as $D \to K^*e\nu$.