Measurements of Lifetimes and a Limit on the Lifetime Difference in the Neutral D-Meson System

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(Received 10 March 1999)

Using the large hadroproduced charm sample collected in experiment E791 at Fermilab, we report the first directly measured constraint on the decay-width difference $\Delta\Gamma$ for the mass eigenstates of the D^0-$\overline{D}^0$ system. We obtain our result from lifetime measurements of the decays $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$, under the assumption of CP invariance, which implies that the CP eigenstates and the mass eigenstates are the same. The lifetime of $D^0 \to K^-K^+$ (the CP-even final state) is $\tau_{KK} = 0.410 \pm 0.011 \pm 0.006$ ps, and the lifetime of $D^0 \to K^-\pi^+$ (an equal mixture of CP-odd and CP-even final states) is $\tau_{K\pi} = 0.413 \pm 0.003 \pm 0.004$ ps. The decay-width difference is $\Delta\Gamma = 2(\Gamma_{KK} - \Gamma_{K\pi}) = 0.04 \pm 0.14 \pm 0.05$ ps^{-1}. We relate these measurements to measurements of mixing in the neutral D-meson system.

PACS numbers: 14.40.Lb, 11.30.Er, 12.38.Qk

The two mass eigenstates of the D^0-$\overline{D}^0$ system may have different lifetimes. In the standard model the dominant contribution to such a difference arises from box-diagram amplitudes involving the exchange of two W bosons. Suppression factors due to the Glashow-Iliopoulos-Maiani mechanism and heavy quark symmetries in QCD lead to the conclusion that these lifetime and mass differences are too small to be measured [1]. Additional standard model contributions from penguin diagrams [2] and long-distance effects [3] are also expected to be negligible. Thus, a measurable difference in the lifetimes [4] or masses would constitute evidence for new physics. In this Letter, we report the first direct search for a lifetime difference in the neutral D-meson system.

Because lifetime and mass differences lead to particle-antiparticle mixing, previous experiments have looked for mixing as evidence of such differences. The rate of mixing is usually characterized by the parameter r_{mix},

 0031-9007/99/83(1)/32(5)$15.00

which is defined as the ratio of mixed to unmixed decays

$$r_{\rm mix} \equiv \frac{\Gamma(D^0 \to \overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f)}\,. \qquad (1)$$

This ratio can have contributions from both the mass difference Δm and the decay-rate difference $\Delta\Gamma$ between the two neutral D mass eigenstates according to

$$r_{\rm mix} = \frac{(\Delta m)^2}{2\Gamma^2} + \frac{(\Delta\Gamma)^2}{8\Gamma^2}\,, \qquad (2)$$

where Γ is the average of the decay rates of the two neutral D mass eigenstates.

To date, particle-antiparticle mixing has been observed only in the strange- and bottom-quark sectors. Previous searches for D^0-$\overline{D}^0$ mixing have set a limit $r_{\rm mix} < 0.50\%$ at 90% confidence level (C.L.) [5]. Inserting this value into Eq. (2) and assuming $\Delta m = 0$, one obtains the limit $(\Delta\Gamma) < 0.48$ ps^{-1} at 90% C.L. [6]. The measurement of $\Delta\Gamma$ reported here is more sensitive than these previous measurements.

If *CP* conservation holds in the D^0-meson system, the even and odd *CP* eigenstates D_1^0 and D_2^0 will be the mass eigenstates; i.e., they will have definite masses m_1 and m_2, and decay widths Γ_1 and Γ_2. Since the Cabibbo-suppressed final state K^-K^+ is *CP* even, it results from the decay (we imply charge-conjugate decay modes throughout) of D_1^0 and will have an exponential decay-rate distribution

$$\Gamma_{KK}(t) = A_{KK}e^{-\Gamma_1 t}, \qquad (3)$$

where here and in Eqs. (4) and (7) below, A represents all time-independent factors. In contrast, the Cabibbo-favored final state $K^-\pi^+$ receives roughly equal contributions from D_1^0 and D_2^0. Under the assumption of *CP* conservation and ignoring doubly Cabibbo-suppressed terms, the decay-rate distribution of a combined sample of $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ (from mixing), and separately a combined sample of $\overline{D}^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^-\pi^+$, can be described by [7,8]

$$\Gamma_{K\pi}(t) = A_{K\pi}e^{-\Gamma t}\cosh\!\left(\frac{\Delta\Gamma}{2}\,t\right), \qquad (4)$$

where

$$\Gamma = (\Gamma_1 + \Gamma_2)/2 \quad \text{and} \quad \Delta\Gamma = \Gamma_1 - \Gamma_2\,, \qquad (5)$$

and so

$$\frac{\Delta\Gamma}{2} = \Gamma_1 - \Gamma = \Gamma_{KK} - \Gamma_{K\pi} = \frac{1}{\tau_{KK}} - \frac{1}{\tau_{K\pi}}\,. \qquad (6)$$

Given the current limits on $\Delta\Gamma$, Eq. (4) is well approximated by a pure exponential distribution

$$\Gamma_{K\pi}(t) = A_{K\pi}e^{-\Gamma t} \qquad (7)$$

over the range of sensitivity of our experiment.

If the mass states are *not CP* eigenstates, i.e., *CP* violation is present, then interpreting the measured lifetime difference in terms of Γ_1 and Γ_2 is less straightforward. However, even in the absence of strict *CP* conservation, pure exponential distributions are still good approximations for both the KK and $K\pi$ distributions in our data sample. In this case, a measured difference at our level of sensitivity would constitute evidence for physics beyond the standard model, although it might not be easily related to the lifetime difference of the mass eigenstates. For convenience of interpretation, we hereafter assume *CP* invariance in the D^0-meson system, though the validity of that assumption has previously been questioned in the literature [9].

The results reported here are based on data accumulated by experiment E791 in a 500-GeV/c π^- beam during the 1991–1992 Fermilab fixed-target run. E791 was the fourth in a series of charm experiments performed in the Fermilab Tagged Photon Laboratory. The E791 spectrometer [10] was an open-geometry detector with 23 planes of silicon microstrip detectors (six upstream and seventeen downstream of the target), 35 drift chamber planes, ten proportional wire chambers (eight upstream and two downstream of the target), two magnets for momentum analysis, two large multicell threshold Čerenkov counters for charged particle identification, electromagnetic and hadronic calorimeters for electron/hadron separation as well as for on-line triggering, and a fast data acquisition system that collected data at a rate of up to 30 Mbyte/s with a 50 μs/event deadtime. The target consisted of a 0.52-mm platinum foil followed by four 1.6-mm diamond foils. Each target center was separated from the next by about 1.5 cm, allowing observation of charm-particle decays in air with minimal background from secondary interactions in the targets. The very loose transverse-energy trigger was based on the energy deposited in the calorimeters and was highly efficient for charm events. Over 2×10^{10} events were recorded during a six-month period.

The measurement of $\Delta\Gamma$ is based on the observation of $D^0 \to K^-K^+$ and $K^-\pi^+$ decay modes in the same detector with similar detector and topological biases and uncertainties, leading to a precise comparison of the lifetimes for the two modes. This is a companion analysis to that of Ref. [11], in which we set limits on *CP* violation and measured the branching ratios for $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ relative to that for $D^0 \to K^-\pi^+$.

Selection requirements for inclusion in the $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$ samples included a minimum significance of separation of the candidate decay vertex from the production vertex in the beam direction ($>8\sigma$ where σ is the uncertainty in the separation of the two vertices). Candidate decay tracks were required to be inconsistent with coming from the D^0 production vertex. The net momentum of the D^0 candidate transverse to the line connecting the production and decay vertices was required to be less than 0.35 GeV/c, and the sum of the p_t^2 of the decay tracks was required to be greater than 0.25 (GeV/c)^2, with p_t measured relative to the direction of the candidate D^0. Finally, to remove secondary interactions, the decay vertex had to be located at least

4σ outside the target foils, where σ is the uncertainty in the position of the decay vertex in the beam direction.

We used particle identification from the Čerenkov counters to improve the statistical significance of the $D^0 \to K^-K^+$ sample. To minimize systematic effects in calculating $\Delta\Gamma$, similar particle identification criteria were applied to the $K^-\pi^+$ sample as well. We obtained the necessary particle-identification efficiencies from a study of the $D^0 \to K^-\pi^+$ sample. We corrected for the Čerenkov counter efficiency by a weighting procedure whereby each two-track candidate decay was weighted by the inverse of the product of the two particle-identification efficiencies calculated for their individual p, p_t, and particle type. Figure 1 shows the weighted invariant mass plots for our final data sample. The numbers of unweighted signal events in the K^-K^+ and $K^-\pi^+$ samples are approximately 3200 and 35 400, respectively.

To account for the effects of our selection criteria, we define a reduced decay length for each D^0 candidate as the distance traveled by the candidate beyond that required to survive our selection criteria, and a reduced proper time corresponding to that reduced decay length. To the extent that the K^-K^+ final state is a mass eigenstate of the neutral D-meson system, its proper-decay-time distribution is purely exponential. In this case, its reduced proper-decay-time distribution is also purely exponential with the same characteristic decay time. In contrast, the $K\pi$ final state is a mixture of mass eigenstates with its proper-decay-time distribution given by Eq. (4). However, since the difference in the decay rates of the eigenstates is small (as known from limits on r_{mix}), the difference in the amount of D_1^0 and D_2^0 contributing to the $D^0 \to K^-\pi^+$ decay after our proper-decay-length cut is negligible. Also, effects of fitting to a single exponential of reduced proper time are smaller by an order of magnitude than the systematic errors described below. We use reduced proper lifetime because it minimizes acceptance corrections and associated systematic errors. We measure the lifetimes over the same range of reduced proper time for both decay modes.

For each bin of reduced proper time, candidates are taken from the total sample shown in Fig. 1, where the signal region is defined as within ± 2.5 Gaussian standard deviations of the Gaussian mean, and the background is taken from sidebands, but at the level of the cross-hatched area. We use the same D^0 mass and Gaussian width in each of the 16 bins of reduced proper time, as determined from Fig. 1 separately for $D^0 \to K^-K^+$(1866.7 and 11.6 MeV/c^2) and $D^0 \to K^-\pi^+$(1867.0 and 13.5 MeV/c^2).

We correct for small acceptance differences between the K^-K^+ and $K^-\pi^+$ final states by using a PYTHIA-based Monte Carlo model [12] that incorporates a full detector simulation. The simulated events are subjected to exactly the same selection criteria and binning as are the data. Figure 2 shows the efficiencies from the Monte Carlo study as functions of the reduced proper decay time for K^-K^+ and $K^-\pi^+$ separately. Figure 3 presents the exponential fits to the measured reduced-proper-decay-time distributions after particle-identification weighting and acceptance corrections. We

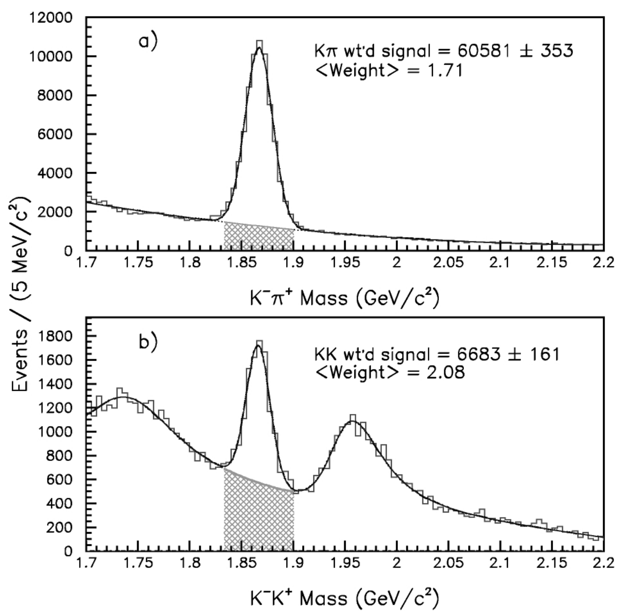

FIG. 1. Invariant mass distribution for candidates weighted by particle identification efficiency (see text). (a) $D^0 \to K^-\pi^+$ decays. The solid line corresponds to a fit to a Gaussian signal distribution plus a third-order polynomial for combinatoric background. (b) $D^0 \to K^-K^+$ decays. The solid line corresponds to a fit to a Gaussian signal distribution plus an asymmetric Breit-Wigner ($D^0 \to K^-\pi^+$ reflection), a symmetric Breit-Wigner ($D^0 \to K^-\pi^+\pi^0$ reflection), and a linear combinatoric background. The cross-hatched areas are the estimated backgrounds beneath our signal region of width ± 2.5 Gaussian standard deviations about the Gaussian mean.

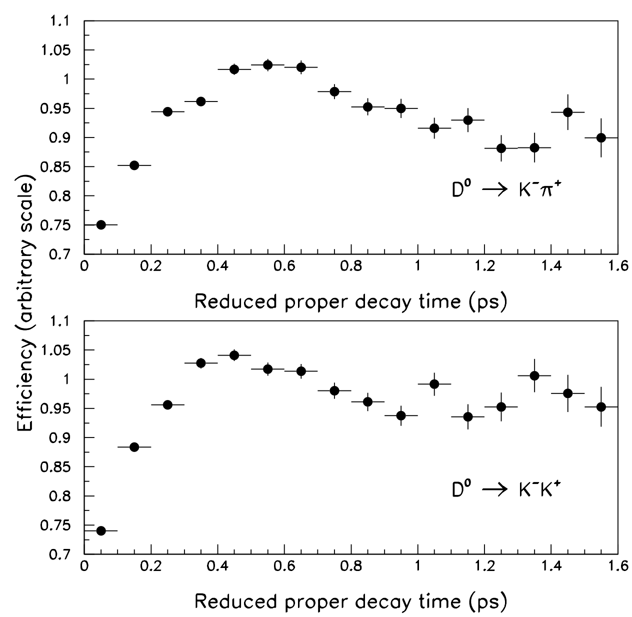

FIG. 2. The $K^-\pi^+$ (top) and K^-K^+ (bottom) efficiencies as functions of the reduced proper decay time. Note that the vertical scales have suppressed zeros.

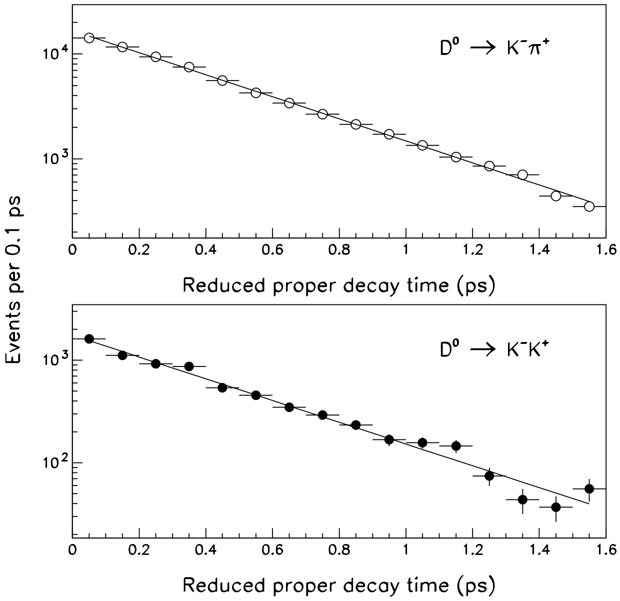

FIG. 3. Distributions and the exponential fits for the number of $D^0 \rightarrow K^-\pi^+$ (top) and K^-K^+ (bottom) decays as a function of reduced proper decay time, after particle identification weighting and acceptance corrections.

measure decay widths $\Gamma_{KK} = 2.441 \pm 0.068\ \text{ps}^{-1}$ and $\Gamma_{K\pi} = 2.420 \pm 0.019\ \text{ps}^{-1}$; or lifetimes $\tau_{KK} = 0.410 \pm 0.011$ ps and $\tau_{K\pi} = 0.413 \pm 0.003$ ps, where the quoted errors are statistical only. Using Eq. (6), we calculate $\Delta\Gamma = 0.04 \pm 0.14\ \text{ps}^{-1}$. We have also performed a joint fit to the distributions using Eqs. (3) and (4), which yields the same result.

Systematic errors are studied separately for the two lifetimes and for the lifetime difference. These studies include the effects of varying the event selection criteria, the D^0 production model used in the Monte Carlo, the particle-identification weighting procedure, the effect of fixing the K^-K^+ width, and fixing the range of reduced proper lifetime over which the fits are done. Estimates of the systematic errors arising from these sources are summarized in Table I. In obtaining systematic errors on $\Delta\Gamma$ from those on the lifetimes, correlation effects are included. For example, different production models lead to similar changes in acceptance for the K^-K^+ and $K^-\pi^+$ modes, resulting in a cancellation in the systematic error in $\Delta\Gamma$. On the other hand, the uncertainties in mass resolution for the K^-K^+ and $K^-\pi^+$ samples come from fits to independent data samples and are uncorrelated, and thus their contribution to the uncertainty in $\Delta\Gamma$ is calculated as the quadratic sum of contributions coming from the uncertainties in the two lifetimes. Systematic uncertainties due to the different absorption cross sections for K and π are negligible, both because the momentum distributions are quite similar and because the targets are very thin.

TABLE I. Contributions to the systematic errors in lifetimes and lifetime difference.

Systematic error in	$\tau_{K\pi}$ (ps)	τ_{KK} (ps)	$\Delta\Gamma$ (ps^{-1})
Fit range	0.002	0.003	0.024
Selection criteria	0.001	0.002	0.020
Particle ID weighting	0.001	0.003	0.024
MC production model	0.003	0.003	0.000
Fixed width	0.001	0.002	0.030
Total	0.004	0.006	0.050

TABLE II. Comparison of our measured lifetimes with previous measurements.

	$\tau_{K\pi}$ (ps)	τ_{KK} (ps)
E791	0.413 ± 0.003 ± 0.004	0.410 ± 0.011 ± 0.006
E687 [13]	0.413 ± 0.004 ± 0.003	···
E691 [14]	0.422 ± 0.008 ± 0.010	···
PDG [6]	0.415 ± 0.004	···

In summary, we measure $\tau_{KK} = 0.410 \pm 0.011 \pm 0.006$ ps and $\tau_{K\pi} = 0.413 \pm 0.003 \pm 0.004$ ps. These results are compared with previous measurements and the world average in Table II. We find $\Delta\Gamma = 0.04 \pm 0.14 \pm 0.05\ \text{ps}^{-1}$, leading to a limit of $-0.20 < \Delta\Gamma < 0.28\ \text{ps}^{-1}$ at 90% C.L. The value of $\Delta\Gamma$ is consistent with zero and thus, at our level of sensitivity, is consistent with the standard model. This measurement gives us, independent of mixing studies, a limit on $\Delta\Gamma$. This 90% C.L. limit on the value of $\Delta\Gamma$ does not saturate the 90% C.L. limit on r_{mix}. If r_{mix} were at its limit, this would have to be due to a contribution from $(\Delta m)^2$.

We gratefully acknowledge the assistance of the staffs of Fermilab and of all the participating institutions. This research was supported by the Brazilian Conselho Nacional de Desenvolvimento Cient' fico e Tecnológico, CONACyT (Mexico), the Israeli Academy of Sciences and Humanities, the U.S. Department of Energy, the U.S.-Israel Binational Science Foundation, and the U.S. National Science Foundation. Fermilab is operated by the Universities Research Association, Inc., under contract with the United States Department of Energy.

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