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Upper Limits on the Decay $D^o \to \mu^+\mu^-$ and on D^o-$\bar{D}^o$ Mixing

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As a by-product to the study of muon pairs produced by 255-GeV/c pions, data from Experiment 615 at Fermilab yield upper limits on the decay $D^o \to \mu^+\mu^-$ and on D^o-$\bar{D}^o$ mixing. An unrestricted sample of 122,630 unlike-sign muon pairs allows a 90% C.L. upper limit of 9.5×10^{-6} to be placed on the branching ratio of the charm-changing neutral-current decay $D^o \to \mu^+\mu^-$. From a sample of 3973 like-sign muon pairs, the ratio $r = \Gamma(\bar{D}^o \to \mu^+X)/\Gamma(\bar{D}^o \to \mu^-X)$ is determined to be $r < 4.7 \times 10^{-3}$ at 90% C.L.

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Historically, the suppression of flavor-changing neutral currents has played a major role in shaping the present theory of the weak and electromagnetic interactions and in predicting the existence of new physics. The low rates for K^o-$\bar{K}^o$ mixing and $K^o_L \to \mu^+\mu^-$ led to the GIM mechanism[1] which in turn predicted the charm quark. As a test of the now-standard $SU(2)_L \times U(1)$ model of electroweak interactions, it is natural to extend the search for flavor-changing neutral currents from the K^o to the D^o sector and look for the decay $D^o \to \mu^+\mu^-$ and for D^o-$\bar{D}^o$ mixing. These processes are expected[2,3] to occur at rates below the current experimental limits.[4,5] An additional motivation is the apparent excess of same-sign kaon events found in D^oD^o decays by the Mark III group.[6] These events may be due to doubly-Cabibbo-suppressed D^o decays or to D^o-$\bar{D}^o$ mixing. Several models have been proposed[7] which allow a larger mixing rate than the standard model.

Experiment 615 at Fermilab was designed to study muon pairs produced in the forward direction in pion-nucleon interactions. Its principle goal was to explore the structure of the pion, by measurement of $\mu^+\mu^-$ pairs with invariant masses greater than 4 GeV/c^2 which arise from quark-antiquark annihilation.[8] In this Letter we use lower-mass $\mu^+\mu^-$ data to search for the decay $D^o \to \mu^+\mu^-$. In addition, we analyze the same-sign muon-pair spectra $(\mu^+\mu^+, \mu^-\mu^-)$ to set limits on D^o-$\bar{D}^o$ mixing, where the production of a $D\bar{D}^o$ pair is followed by the semi-leptonic decays of both mesons to μ^+X and the decay $\bar{D}^o \to \mu^+X$ results from D^o-$\bar{D}^o$ mixing.

The experimental apparatus has been described in detail elsewhere.[9] Briefly, the 255-GeV/c pion beam interacted in a tungsten target just upstream of a selection magnet, whose magnetic volume was filled with low-Z material to absorb secondary hadrons. Downstream of the selection magnet was a magnetic spectrometer consisting of 16 planes of drift chambers, 9 planes of multi-wire proportional chambers, and 4 scintillator hodoscopes surrounding an analysis magnet. Candidate track pairs were required to penetrate an additional 2 m of iron at the rear of the apparatus to confirm that they were muons. A hardware processor used hodoscope information to trigger only on muon pairs with invariant mass above 2.0 GeV/c^2. In addition, there was a prescaled trigger on every thousandth muon pair regardless of mass. Data were obtained in runs of 5.5×10^{13} π^- and 3.8×10^{13} π^+ beam particles at 255 GeV/c.

The decay $D^o \to \mu^+\mu^-$ (and $\bar{D}^o \to \mu^+\mu^-$), if present, would result in an enhancement at the D^o mass in the $\mu^+\mu^-$ spectrum. Figure 1(a) shows the raw mass distribution from the 122,630 muon pairs in the prescaled-trigger sample, which is well suited to a search at lower masses because of the absence of a hardware mass cut. These pairs were required to pass the following criteria: (i) 2 and only 2 opposite-sign reconstructed tracks; (ii) total pair momentum < 280 GeV/c; (iii) individual track momenta < 260 GeV/c.

The solid line in Figure 1(a) is a fit to the data using Gaussian distributions for pairs due to J/ψ, ψ', and D^o decays, and an exponential of a quartic polynomial to describe the continuum mass distribution. The fit was performed in the mass interval $1.0 < M < 5.0$ GeV/c^2 (where the acceptance was slowly varying) and has a χ^2 of 178.6 for 150 degrees of freedom. The χ^2 is 64.9 for 60

degrees of freedom in the mass interval $1.0 < M < 2.75$ GeV/c^2. The fitted J/ψ mass, $M_J = 3.080 \pm 0.003$ GeV/c^2, is somewhat low due to the energy loss of muons via bremsstrahlung and pair production. The fitted J/ψ mass resolution is 0.165 ± 0.003 GeV/c^2, compatible with the calculation of 0.170 GeV/c^2 made with a Monte Carlo simulation of the apparatus. Figure 1(b) is a plot of the data with the fitted parameterization (except for the D^o contribution) subtracted. The solid line represents the best fit when D^o and $\bar{D}^o$ decays are included at 90% confidence level. The mass resolution of the $D^o(1865)$ was set to 0.165 GeV/c^2, consistent with the detector resolution.

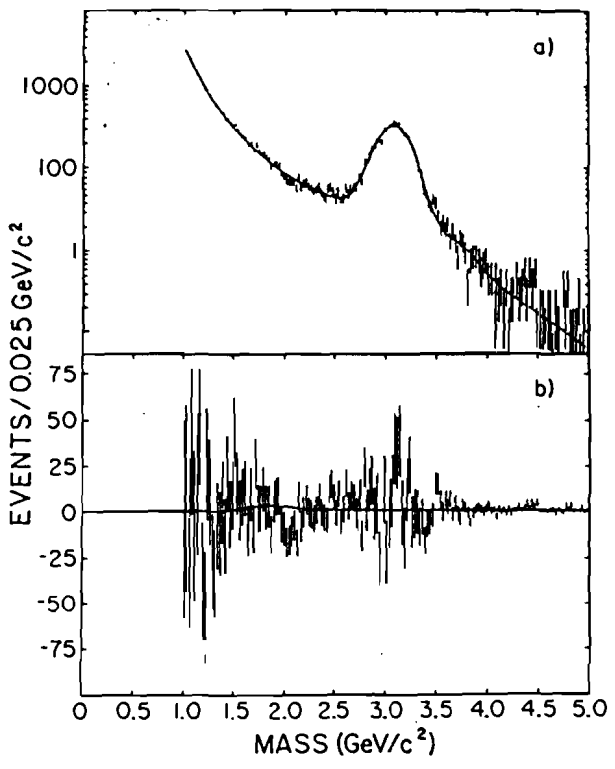

FIG. 1. (a) The raw mass distribution from the prescaled-trigger sample. The solid line is a fit to the data described in the text. (b) The raw mass distribution with the fitted parameterization subtracted. The solid line is the best fit when D^o and $\bar{D}^o$ decays are included at 90% C.L.

An upper limit on the decay $D^o \to \mu^+\mu^-$ was obtained by normalizing to J/ψ events according to

$$\frac{\Gamma(D^o \to \mu^+\mu^-)}{\Gamma(D^o \to \text{all})} = \frac{\sigma \cdot B(J \to \mu^+\mu^-)}{\sigma(D^o) + \sigma(\bar{D}^o)} \frac{N_{D^o} + N_{\bar{D}^o}}{N_J} \frac{A_J}{A_{D^o}},$$

where Γ is the decay rate. The cross-section-times-branching-ratio for J/ψ production was measured by our experiment[10] to be $\sigma \cdot B(J \to \mu^+\mu^-) = 8.15 \pm 0.76$ nb/nucleon for Feynman-x (x_F) > 0. The observed number of J/ψ decays in the prescaled-trigger sample was $N_J = 5584 \pm 200$, and the upper limit on the observed number of D^o and $\bar{D}^o$ decays at 90% C.L. was $N_{D^o} + N_{\bar{D}^o} \leq 48.6$. The total $J/\psi \to \mu^+\mu^-$ acceptance was calculated to be $A_J = 0.055 \pm 0.003$.

The D cross sections were taken from four experiments which recently measured $D\bar{D}$ production in $\pi^- N$ interactions[11-14] with a variety of targets and beam energies. A summary of the results is shown in Table 1. Averaging over the four experiments, we estimate that $\sigma(D) + \sigma(\bar{D}) = 18.2 \pm 1.9$ μb/nucleon for $x_F > 0$, assuming a linear dependence on the atomic number of the target. The data from the ACCMOR[13] and LEBC-EHS[14] groups suggest that $\sigma(D^o) + \sigma(\bar{D}^o) > \sigma(D^+) + \sigma(D^-)$, which is expected since the D^* decays predominantly to D^o and $\bar{D}^o$. Nevertheless, we conservatively assume that the charged and neutral cross sections are the same and obtain $\sigma(D^o) + \sigma(\bar{D}^o) = 9.1 \pm 1.0$ μb/nucleon.

TABLE 1. Measurements in $\pi^- N$ interactions of inclusive D production for $x_F > 0$, presented in the form $d^2\sigma/dx_F dP_T^2 \sim [A(1-x_F)^{n_1} + B(1-x_F)^{n_2}]e^{-bP_T^2}$.

	Ref. 11	Ref. 12	Ref. 13	Ref. 14
$\sigma(D)+\sigma(\bar{D})$ (μb)	28 ± 11	$13.8^{+3.0}_{-2.5}$	$24 \pm 7.5 \pm 12$	15.8 ± 2.7
Target	C_3F_8	Fe	Be	H
Energy (GeV)	340	278	175/200	360
b	~ 1.23	0.70 ± 0.15	1.1 ± 0.5	1.18 ± 0.18
A	--	~ 0.46	--	~ 0.34
n_1	~ 0.7	~ 0.9	0.8 ± 0.4	~ 0.7
B	--	~ 5.2	--	~ 6.8
n_2	--	~ 5.9	--	~ 7.5

The total acceptance for $D^o \to \mu^+\mu^-$ was calculated to be $A_{D^o} = 0.0462 \pm 0.0046$, assuming a distribution of the form $d^2\sigma/dx_F dP_T^2 \sim (1-x_F)^3 e^{-1.0P_T^2}$ for D production, which is consistent with the measurements of the CCFRS[12] and LEBC-EHS[14] groups. (The total acceptance would be 0.0686 ± 0.0069 for a $(1-x_F)^2$ distribution, which is closer to the measurements of the BIBC[11] and ACCMOR[13] groups.) Finally, it was assumed that the ratio of the cross sections for D and J/ψ production in K-N and p-N interactions is the same as in π-N interactions, even though the J/ψ production cross section by pions is approximately twice that by protons.[15] We therefore counted the kaon and proton contamination in the beam (which averaged 5.2% and 19.6%, respectively) as pions.

Combining the above factors, we find the 90% C.L. limit on the branching ratio to be

$$\Gamma(D^o \to \mu^+\mu^-)/\Gamma(D^o \to \text{all}) < 9.5 \times 10^{-6},$$

where the percentage errors have been added in quadrature. The main uncertainty in calculating this limit is

the total acceptance, A_{D^o}, for $D^o \to \mu^+\mu^-$, which depends on the D production distribution. Although there is some disagreement among the experiments concerning the x_F distribution , we have conservatively chosen a relatively central x_F spectrum to estimate A_{D^o}. The EMC group has recently[4] set an upper limit of 3.4×10^{-4} on this branching fraction.

As mentioned above, the $\mu^+\mu^+$ spectrum[16] might contain a component due to the production and semi-leptonic decay of a $D\bar{D}^o$ pair in which the decay $\bar{D}^o \to \mu^+X$ occurs via D^o-$\bar{D}^o$ mixing. To search for mixing we found it most effective to examine the $|\cos\theta|$ distribution of the pairs, where θ is the angle between the direction of the incident pion and a μ^+ in the muon-pair rest frame. Figure 2 shows the $|\cos\theta|$ distribution of the 3973 $\mu^+\mu^+$ pairs with mass > 2.0 GeV/c^2 belonging to the full data sample, for which the hardware mass cut was enforced. In addition to satisfying criteria similar to those for the prescaled-trigger sample described above, pairs in the full data sample were required to have muon tracks at angles of at least 8 mr relative to the incident pion beam, to avoid contamination by muons from beam-particle decays.

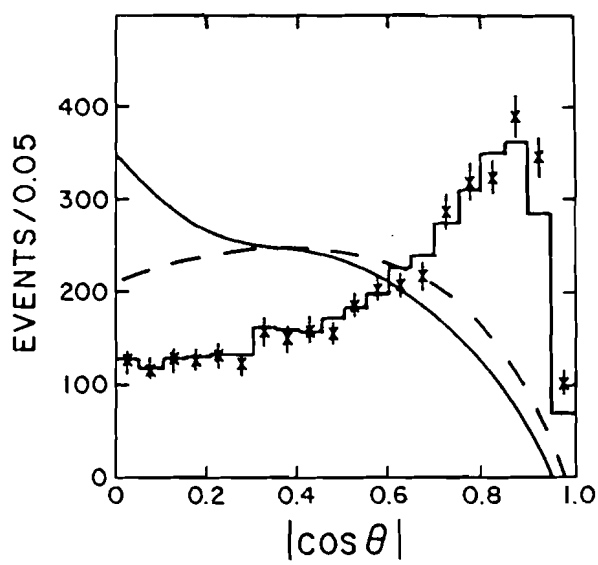

FIG. 2. The $|\cos\theta|$ distribution for like-sign muon pairs (points with error bars). The histogram is from the random-pair sample. The dashed and solid lines are predictions arising from D^o-$\bar{D}^o$ mixing in parameterizations A and D, respectively, described in the text.

The histogram in Figure 2 was obtained from the 'random-pair sample.' This was generated by taking a muon in the prescaled-trigger sample which was not part of an in-time opposite-sign muon pair and randomly combining it with another such muon. The excellent agreement between the directly observed $\mu^+\mu^+$ data and the random-pair sample suggests that the like-sign muon pairs were essentially all due to uncorrelated background, probably from separate pion and/or kaon decays. Since the average pion multiplicity in a RF 'bucket' was about 5, the muons from uncorrelated background came mostly from different pion interactions.

We used a Monte Carlo simulation to calculate the $|\cos\theta|$ distribution of $\mu^+\mu^+$ pairs from $D\bar{D}^o$ decay with D^o-$\bar{D}^o$ mixing. To perform this simulation we needed to know the differential cross section for the associated production of $D\bar{D}^o$ pairs, as well as the muon spectra from the semi-leptonic decays of the D mesons. The latter were taken from the work of Ali,[17] assuming contributions from $D \to K\mu\nu$, $D \to K^*(890)\mu\nu$, and $D \to \pi\mu\nu$ of 55%, 39%, and 6%, respectively.[18] For $D\bar{D}$ associated production we considered four different parameterizations:

A. Uncorrelated $D\bar{D}$ production with each D generated by $d^2\sigma/dx_F dP_T^2 \sim (1-x_F)^3 e^{-1.0P_T^2}$ for $x_F > 0$.

B. Uncorrelated $D\bar{D}$ production with each D generated by $d^2\sigma/dx_F dP_T^2 \sim (1-x_F)^2 e^{-1.0P_T^2}$ for $x_F > 0$.

C. Uncorrelated $D\bar{D}$ production with each D generated by $d^2\sigma/dx_F dP_T^2 \sim [0.46(1-x_F)^{0.9} + 5.2(1-x_F)^{5.9}]e^{-0.7P_T^2}$ for $x_F > 0$.

D. Correlated $D\bar{D}$ production with the D's produced from the decay of a heavier state M generated by $d^3\sigma/dM dx_F dP_T^2 \sim e^{-0.55M} M^{-3}(1-x_F)^1 e^{-1.0P_T^2}$. This yields a distribution $\sim (1-x_F)^3$ for each D.

Parameterization A is consistent with the measurements of the CCFRS[12] and LEBC-EHS[14] groups while B is closer to the measurements of the BIBC[11] and ACCMOR[13] groups. Parameterization C comes directly from the CCFRS[12] group, which had a beam energy and target material similar to ours. Parameterization D is representative of correlated $D\bar{D}$ production.

The dashed and solid curves in Figure 2 are the $\mu^+\mu^+$ spectra predicted by combining D^o-$\bar{D}^o$ mixing with parameterizations A and D, respectively. They have a completely different shape from the data. To determine quantitatively what fraction of the $\mu^+\mu^+$ data could be due to D^o-$\bar{D}^o$ mixing, the data were fitted to a sum of random-pair sample and Monte-Carlo-generated D^o-$\bar{D}^o$ mixing events. The results of the fit are shown in Table 2 for the four different parameterizations. The χ^2 is 25.6 for 18 degrees of freedom for each fit. Not more than 63 events are consistent with D^o-$\bar{D}^o$ mixing at 90% C.L..

The upper limit on D^o-$\bar{D}^o$ mixing (normalized to J/ψ events) is given by

$$r = \frac{\Gamma(\bar{D}^o \to \mu^+X)}{\Gamma(D^o \to \mu^-X)} = \frac{\sigma \cdot B(J \to \mu^+\mu^-)}{\sigma(D\bar{D}^o) \cdot B_D B_{D^o}} \frac{N_{D\bar{D}^o}}{N_J} \frac{A_J}{A_{D\bar{D}^o}}.$$

The cross-section-times-branching-ratio for J/ψ production is given above. The number of J/ψ decays observed in the full data sample was $N_J = (2.20 \pm 0.10) \times 10^6$. The total $J/\psi \to \mu^+\mu^-$ acceptance was calculated to be $A_J = 0.0307 \pm 0.0016$, taking into ac-

count the more restrictive trigger and analysis requirements of the full data sample. For the $D \to \mu X$ semi-leptonic branching ratios we used measurements by the Mark III collaboration[19] of $B_D = (11.7 \pm 1.1)\%$ and $B_{\bar{D}^o} = (7.5 \pm 1.2)\%$. We assumed that a $\bar{D}^o$ was always accompanied by a D^+ or D^o with equal probability. A neutral-D cross section larger than the charged-D cross section, or significant $\Lambda_c^+ \bar{D}$ production,[20] would imply a lower semi-leptonic branching ratio; however, this would be offset by a relatively larger $\bar{D}^o$ cross section. Hence the cross section for a $D\bar{D}^o$ pair was taken to be $\sigma(D\bar{D}^o) = \sigma(\bar{D}^o) = 4.5 \pm 0.5$ μb/nucleon. The total acceptance for $D_{\searrow \mu^+ X} \bar{D}^o_{\searrow \mu^+ X}$, $A_{D\bar{D}^o}$, the number of possible D^o-$\bar{D}^o$ mixing events at 90% confidence level, $N_{D\bar{D}^o}$, and the resulting limits are shown in Table 2 for the four different parameterizations.

TABLE 2. Total acceptances, limits on the number of mixing events, and limits on $r = \Gamma(\bar{D}^o \to \mu^+ X)/\Gamma(\bar{D}^o \to \mu^- X)$ for four parameterizations of $D\bar{D}$ production described in the text.

Param.	Total Acceptance	Limit on Mixing Events	Limit on r
A	$3.3 \pm 0.3 \times 10^{-5}$	52.1	4.7×10^{-3}
B	$4.6 \pm 0.5 \times 10^{-5}$	43.6	2.8×10^{-3}
C	$4.5 \pm 0.5 \times 10^{-5}$	62.9	4.2×10^{-3}
D	$6.8 \pm 0.7 \times 10^{-5}$	43.8	1.9×10^{-3}

To set a limit we take the $D\bar{D}$ production parameters from parameterization A and conclude that at 90% C.L.,

$$r = \Gamma(\bar{D}^o \to \mu^+ X)/\Gamma(\bar{D}^o \to \mu^- X) < 4.7 \times 10^{-3},$$

where the percentage errors have been added in quadrature. A possible source of systematic error is the estimate of the total acceptance, $A_{D\bar{D}^o}$. Our acceptance is greater for correlated $D\bar{D}^o$ production at high x_F and lower for uncorrelated production at low x_F. To be conservative we have based our limit on parameterization A which produces an uncorrelated $D\bar{D}^o$ pair with a central x_F spectrum. The previous best limit[5] is $r < 1.2 \times 10^{-2}$. Predictions[3] of r lie in the range 10^{-4} to 10^{-12}. Analysis of D^o-$\bar{D}^o$ mixing indicates that $r = (4\Delta M^2 + \Delta\Gamma^2)/(8\Gamma^2 + 4\Delta M^2 - \Delta\Gamma^2)$, where ΔM and $\Delta\Gamma$ are the differences in the masses and widths of the two CP eigenstates of the D^o and Γ is the average width.[21] For $\Gamma = 2.27 \times 10^{12}$/sec,[22] and $r < 4.7 \times 10^{-3}$, we obtain $\Delta M < 1.5 \times 10^{-4}$eV/c^2 and $\Delta\Gamma/\Gamma < 0.19$.

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