LIMITS ON D^0–$\bar{D}^0$ MIXING AND BOTTOM PARTICLE PRODUCTION CROSS SECTION FROM HADRONICALLY PRODUCED SAME-SIGN DIMUON EVENTS ☆

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Received 21 January 1982

The rates for same-sign and opposite-sign dimuon events with missing energy (indicative of final-state neutrinos) have been measured in 278 GeV π^-–Fe and 350 GeV proton–Fe collisions. The main source of opposite-sign events is two semileptonic decays of hadronically produced charm states. The same-sign events are consistent with background from pion and kaon decays. We obtain a limit of 0.044 (90% CL) on the fraction of D^0 semileptonic decays that result in the wrong-sign muon and conclude that less than 9% (90% CL) of same-sign dimuon events produced in neutrino interactions can be attributed to D^0–$\bar{D}^0$ mixing. The data imply $\delta m < 6.5 \times 10^{-4}$ eV and $\delta\lambda/\lambda < 0.55$ for the difference in mass and inverse lifetime of the *CP* eigenstates of the D^0. Limits on diffractive bottom production cross sections in proton and pion collisions are also presented.

The rate of prompt same-sign dimuon events in neutrino interactions has been measured to be about 10% to 14% of the rate of opposite-sign dimuon events [1]. Such a high rate is presently not understood. For example, theoretical calculations [2] of associated charm production via the QCD process of gluon bremsstrahlung yield rates which are one to two orders of magnitude lower than the experimental results. This has led to speculations [3] that D^0–$\bar{D}^0$ mixing [4] is a possible source of the same-sign events. Although D^0–$\bar{D}^0$ mixing is expected to be small in the standard GIM model [5], other models have been proposed in which the mixing can be larger [3]. The experimental limit on D^0–$\bar{D}^0$ mixing obtained from e^+e^- data [6] is 0.16 for the fraction of D^0 mesons

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☆ Supported by the Department of Energy and the National Science Foundation.

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which decay as if they were $\bar{D}^0$. The limit obtained from a study of the photoproduction of D^0_0 mesons [7] is 0.11 and a limit of 0.20 has been obtained by the European Muon Collaboration [8] from the study of wrong-sign trimuon events with missing energy in deep inelastic muon–nucleon scattering. Therefore, the possibility that a substantial fraction of neutrino induced same-sign dimuon events can be due to D^0–$\bar{D}^0$ mixing has not been ruled out by the present experimental limits. In this communication we present data on same-sign dimuon events produced in hadronic reactions. We extract limits on D^0–$\bar{D}^0$ mixing and rule out D^0–$\bar{D}^0$ mixing as a significant source of neutrino-induced same-sign events. In addition we obtain limits on bottom particle production in hadronic collisions.

In the preceding communication [9] we presented results on the study of $\mu^+\mu^-$ pairs with missing energy produced in 350 GeV p–Fe and 278 GeV π^-–Fe interactions. Such events [9,10] come mostly from the double semileptonic decays in associated production of charm states. In this paper we report on the same-sign events and their possible origin. The details of the apparatus and the analysis of the dimuon data are reported in the preceding letter [9]. Briefly, a hadron beam is directed at an iron-scintillator calorimeter that serves as a target and measures the total hadronic and electromagnetic energy of each interaction. The calorimeter is followed by a muon identifier and a solid steel toroidal magnet spectrometer. The trigger required the penetration of at least one muon to the back of the toroid spectrometer system, corresponding to a minimum energy of about 20 GeV. In the analysis of the dimuon sample [9], the second muon was required to traverse at least one third of the toroid spectrometer system (i.e. a minimum energy of 12 GeV). The total measured energy distributions ($E_{\text{calorimeter}} + E_{\text{muons}}$) for dimuon events, show 59 $\mu^+\mu^-$ and no $\mu^+\mu^+$ or $\mu^-\mu^-$ events with more than 45 GeV of missing energy in the 350 GeV proton data sample. The corresponding number of dimuon events with more than 40 GeV of missing energy in the 278 GeV pion data sample are one $\mu^+\mu^+$, two $\mu^-\mu^-$ and 154 $\mu^+\mu^-$ events. These are for a total incident flux of 1.72×10^9 proton interactions and 1.63×10^9 pion interactions in the target calorimeter. As discussed in ref. [9], more than 90% of the $\mu^+\mu^-$ events originate from charm particle decays.

Same-sign dimuon events with missing energy can come from three sources:

(1) An additional π or K decay in association with a single-muon event (the single-muon event can be from charm or pion decay).

(2) D^0–$\bar{D}^0$ mixing, i.e., charm production followed by two semileptonic decays with one D^0 decaying to the wrong-sign muon.

(3) Bottom particle production in which one B particle decayed semileptonically and the other B particle decayed to charm followed by a semileptonic decay of the charm particle.

The background from π and K decays can be determined experimentally from the rate of single-muon events with missing energy and the probability that the remaining particles in the hadron shower yield a wrong-sign muon satisfying the selection criteria on the second muon. That probability was determined as a function of the total *hadron shower energy* in separate runs using a lower energy muon trigger. This calculation neglects the additional missing energy carried by the neutrino in the decay of the second pion, and therefore *underestimates* the background. The calculation yields a background of 1.1 ± 0.1 and 1.9 ± 0.1 ($\mu^+\mu^+ + \mu^-\mu^-$) events for the proton and pion data samples, respectively. If the effect of the second neutrino is included then the corresponding numbers increase to 1.5 and 2.6 events for protons and pions, respectively. We therefore conclude that all the same-sign events observed in our data are consistent with backgrounds from π and K decays. In the subsequent discussion we use the smaller numbers in order to obtain a conservative upper limit on the number of prompt same-sign events.

After subtracting the background and combining the two data samples together we obtain [‡1,2] a 90% CL upper limit of 1.8% for the fraction of prompt same-sign dimuon events with missing energy in hadronic collisions. If the fragmentation of charm quarks to D mesons is independent of whether the charm quark was created in a neutrino or hadronic interaction, then the fraction of D^0 mesons in the two final states is the same. Under that assumption there would be half as many same-sign events from D^0–$\bar{D}^0$ mixing

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[‡1] It is obtained from a 90% upper limit of 6.6 same-sign events when the observed number is 3 and subtracting 3 events from background sources.

[‡2] The number of $\mu^+\mu^-$ events from charm after background subtractions is 192.

in neutrino interactions as in hadronic collisions.

$$(N_{\mu^-\mu^-}/N_{\mu^-\mu^+})_\nu = \tfrac{1}{2}[(N_{\mu^+\mu^+}+N_{\mu^-\mu^-})/N_{\mu^+\mu^-}]_{\text{hadronic}} \leqslant 0.8\%\ (90\%\ \text{CL})\,. \qquad (1)$$

The above is therefore an upper limit on the fraction of $\mu^+\mu^-$ events in neutrino interactions that will be observed as same-sign events due to D^0–$\bar{D}^0$ mixing. Since the observed rate for same-sign events in neutrino experiments [1] is about 10% of the $\mu^+\mu^-$ rate, this implies that less than 9% of neutrino-induced same-sign events can be due to possible D^0–$\bar{D}^0$ mixing.

The fragmentation of a charm quark to mesons can depend on its energy. Therefore, the fraction of D^0's in hadronic and neutrino produced charm may be different due to energy differences. We discuss below two different production models and show that with reasonable assumptions, such differences can change the above limit by at most a factor of two.

In order to extract a limit on D^0–$\bar{D}^0$ mixing [i.e. the relative probability that a D^0 will decay to the wrong-sign rather than the right-sign muon, $P(D^0 \to \bar{D}^0)$] we need to make assumptions about (a) the probabilities that a charm quark fragments to D^0, D^+, F^+ or Λ_c, and (b) the semileptonic branching ratio of the D^0 relative to those of the other charm states. If we assume that the fragmentations of the charm quark and charm antiquark are independent then

$$P(D^0 \to \bar{D}^0) = \frac{1}{2}\,\frac{N_{\mu^+\mu^+}+N_{\mu^-\mu^-}}{N_{\mu^+\mu^-}}\,\sum_0^3 f_iB_i \Big/ f_0B_0\,, \qquad (2)$$

where f_0, f_1, f_2, f_3 and B_0, B_1, B_2, B_3 are the relative production probabilities of D^0, D^+, F^+, Λ_c and their semileptonic branching ratios, respectively. The available data on charm particle semileptonic decays is $B_0 < 4\%$ (90% CL) and $B_1 = 22.0^{+4.4}_{-2.2}\%$ from the DELCO [11] group; and $B_0 = 5.5 \pm 3.7\%$ and $B_1 = 16.8 \pm 6.4\%$ from the Mark II group [12]. Other information on semileptonic decays is available if we assume that the ratios of the semileptonic branching ratios are proportional to the lifetimes. An average of the available data on charm particle lifetimes [‡3] (in units of 10^{-13} s) is

$$\tau(D^0) = 2.8 \pm 0.6\,, \quad \tau(D^+) = 8.1 \pm 1.4\,,$$
$$\tau(F^+) = 2.0^{+1.8}_{-0.8}\,, \quad \tau(\Lambda_c) = 1.4^{+0.8}_{-0.4}\,. \qquad (3)$$

The ratios of the lifetimes are consistent with the ratios of measured semileptonic branching fractions.

The fractions of different charm particles produced in the fragmentation of charm quarks are obtained from two different models. In model A, $f_0(D^0) = 0.35$, $f_1(D^+) = 0.35$, $f_2(F^+) = 0.15$ and $f_4(\Lambda_c) = 0.15$ are assumed. Such production ratios are expected far above threshold where high-mass D^* mesons are expected to decay with equal probability to charged and neutral D's [‡4]. In model B, $f_0(D^0) = 0.55$, $f_1(D^+) = 0.15$, $f_2(F^+) = 0.15$ and $f_4(\Lambda_c) = 0.15$ are assumed. Such fragmentation is expected close to threshold [‡4] [16] where the lowest-mass D^* mesons decay preferentially to neutral D's due to phase-space isospin-violating restrictions.

If the semileptonic branching ratios are proportional to the lifetimes, then using the lifetimes [eq. (3)] and eq. (2) in combination with our data [eq. (1)] yield upper limits (90% CL) of

$$P(D^0 \to \bar{D}^0) < 0.044 \quad (\text{Model A})\,,$$
$$< 0.022 \quad (\text{Model B})\,, \qquad (4)$$

where the limits include the uncertaintly in the lifetime measurements.

The indications from present neutrino emulsion data [‡3,5] are that charm production ratios may be closer to the predictions of model B since substantial D^* production is observed [‡5]. However, to be more conservative we use model A and quote a upper limit of 0.044 on the fraction of D^0 semileptonic decays that result in a wrong-sign muon. Within the standard

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[‡3] For a review of charm particle lifetime see Foa [13]. The F^+ and Λ_c lifetimes come from the E531 collaboration [14] and Stanton [15]. The D^0 lifetime is the average of $3.2^{+1.0}_{-0.7}$(E531), $3.2^{+2.2}_{-1.0}$(LEBC) and $1.9^{+1.7}_{-0.6}$(SLAC 40″ BC); the D^+ lifetime is the average of $9.5^{+6.5}_{-3.3}$(E531), $8^{+4.9}_{-2.9}$ (LEBC), $6.5^{+6.0}_{-2.1}$(SLAC 40″ BC) and $8.1^{+2.0}_{-1.3}$(NA1).

[‡4] Far above threshold equal production of D^0 and D^+ is expected. We assume some suppression of F's due to the heavier mass of the s quark and a small fraction of charm baryon production. Near threshold production of D^{*0}, D^{*+}, D^0 and D^+ is expected according to their spin weight (3, 3, 1, 1). Since the D^{*0} decays only to D^0 and the D^{*+} decays 2/3 to D^0 and 1/3 to D^+ there are three times as many D^0 as D^+. We have assumed that F^* and F mesons to be produced at about half the rate of D^{*0} and D^0. For details see Rosner [16].

[‡5] The emulsion experiment of Ushida et al. [17] reports substantial D^* production in neutrino interactions [18].

GIM model [3,5,19] this fraction is expected to be less than 0.0025 ($<\sin^4\theta_c$).

In general, the fraction of wrong-sign muons is related [3,19] to the difference in mass δm and the difference in inverse lifetimes $\delta\lambda$ for the *CP* eigenstates of the D^0

$$P(D^0-\bar{D}^0)=\frac{\delta m^2+\frac{1}{4}\delta\lambda^2}{2\lambda^2+\delta m^2-\frac{1}{4}\delta\lambda^2}\leqslant 0.044\,,$$

where λ is the average inverse lifetime of both D^0 states. Using $\lambda=(1/2.8)\times 10^{13}$ s we obtain the limit

$$\delta m\leqslant 1\times 10^{12}\,\hbar\,\mathrm{s}^{-1}\quad(=6.5\times 10^{-4}\ \mathrm{eV})\,.$$

This can be compared with the measured $K_L^0-K_S^0$ mass difference of $0.5\times 10^{10}\,\hbar\,\mathrm{s}^{-1}$. Our data also imposes the limit $\delta\lambda/\lambda<0.55$ on the difference in the inverse lifetimes of the *CP* eigenstates of the D^0.

The same-sign dimuons can also be used to investigate bottom particle production in hadronic collisions. Recent measurements at the CERN Intersecting Storage Rings (ISR) indicate that forward production cross sections are large and are in the several hundred μb range for charm [19] [‡6], in the tens of μb range for bottom [21]. Brodsky et al. [22] have suggested a model with an intrinsic charm component in the nucleon wave function of 1% and intrinsic bottom component of 0.1%. The model predicts [22] [‡7] that at ISR energies diffractive charm and bottom cross sections are 400 μb and 20 μb, respectively. Similarly charm and bottom cross sections are predicted [22] [‡7] to be 210 μb and 3 μb for 350 GeV protons and 90 μb and 0.18 μb for 278 GeV pions, respectively.

This experiment is sensitive to forward production of bottom states because it triggers on energetic muons. Our $\mu^+\mu^-$ data can accommodate an *intrinsic charm* diffractive cross section of no more than 3 μb. To extract limits on *intrinsic bottom* we assume that Feynman x distributions for the Λ_b, $\bar{B}$ (for protons) and B, $\bar{B}$ (for pions) are peaked near $x=0.5$ and are the same as for intrinsic charm [22]. The muon and neutrino momentum distributions for B decays were obtained from CESR data [23] [‡8]. The semileptonic branching ratios for $B\to\mu X$ and $\bar{B}\to(D\to\mu X)X$ were taken to be 10% and 8%, respectively [23]. The corresponding branching ratios for $\Lambda_b\to\mu X$ and $\Lambda_b\to(\Lambda_c$ or $D\to\mu X)X$ were assumed to be 10% and 6%, respectively.

Table 1

Limits on diffractive bottom particle production cross sections from $\mu^+\mu^+$ and $\mu^-\mu^-$ events. The atomic weight dependence of the cross section is assumed to be $A^{2/3}$. The quoted limits are twice the cross section for $x>0$ (to account for $x<0$ production).

Beam	Acceptance (%)	$\sigma_{B\bar{B}}$ (nb)
278 GeV π^-	9	< 140
350 GeV p	11	< 40

Using 1.2 events and 4.7 events as the 90% CL upper limit for the number of prompt same sign events in the proton and pion data samples, respectively, we obtain the limits on diffractive bottom production cross sections listed in table 1. Also listed in table 1 are the calculated acceptances for the production model. The atomic weight dependences of the cross sections were assumed to be $A^{2/3}$ for diffraction [22]. If $A^{1.0}$ were assumed (as suggested by other authors [24] than the diffractive limits are reduced by a factor of 3.8. It should be noted that all limits obtained from muon final states depend on the assumed semileptonic branching ratios.

Our results show that intrinsic bottom diffractive cross sections at Fermilab energies are small. Limits for *central* $B\bar{B}$ production cross sections have been obtained by other experiments from studies of multimuon final states in 400 GeV p–Fe [25] and 225 GeV π^-–Be [26] interactions.

In conclusion the low rate of same-sign dimuon events with missing energy produced in hadronic collisions puts limits on $D^0-\bar{D}^0$ mixing and indicates

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[‡6] For a review af hadronic charm production, see ref. [20].

[‡7] Brodsky's model [22] with 1% intrinsic charm predicts

$$\sigma_{c\bar{c}}=0.01\times\sigma_T\{\ln(0.2s/M_{c\bar{c}}^2)/\ln[0.2(53)^2/M_{c\bar{c}}^2]\}\,,$$

$$\sigma_{B\bar{B}}=0.01\times\sigma_T\,(M_c/M_b)^2\times\{\ln(0.2s/M_{B\bar{B}}^2)/\ln[0.2(53)^2/M_{c\bar{c}}^2]\}\,.$$

We have used $\sigma_T=40$ mb and $\sigma_T=20$ mb for p–p and π–p total cross sections, $M_c=1.5$ GeV, $M_b=5$ GeV, $M_{c\bar{c}}=5$ GeV, $M_{B\bar{B}}=10$ GeV, s is the square of the center of mass energy [$s=(53)^2$ at the ISR].

[‡8] We have used the CLEO Monte Carlo which reproduces the multiplicities for $B\to DX$ and the final state lepton momentum distributions for $B\to\mu X$ as measured at the $\Upsilon(4S)$ resonance in e^+e^- interactions (see ref. [23].

that bottom particle production cross sections are small.

We would like to thank Fermilab for its support. One of us (AB) would like to thank the Alfred P. Sloan Foundation for its support. This work was supported by the US Department of Energy and the National Science Foundation.

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